saes high vacuum

Non-evaporable getter (NEG) technology for HV and UHV applications

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OUTLINE

SAES Group and the High Vacuum Division

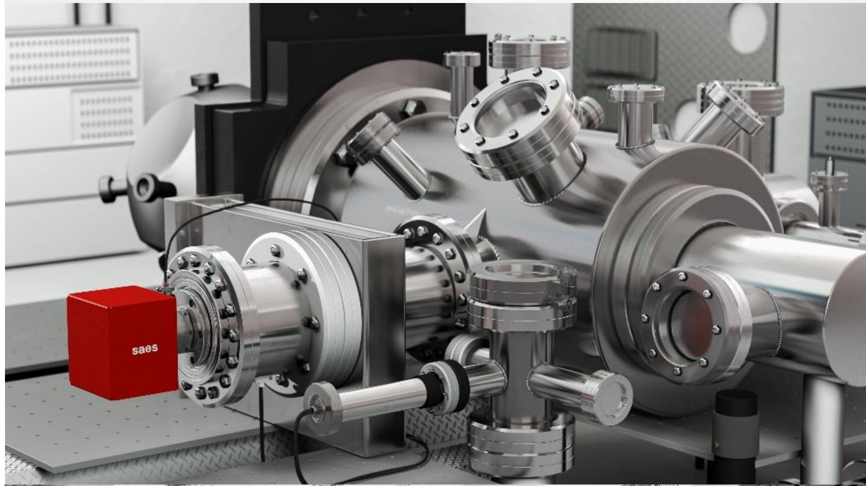
SAES® Core Business

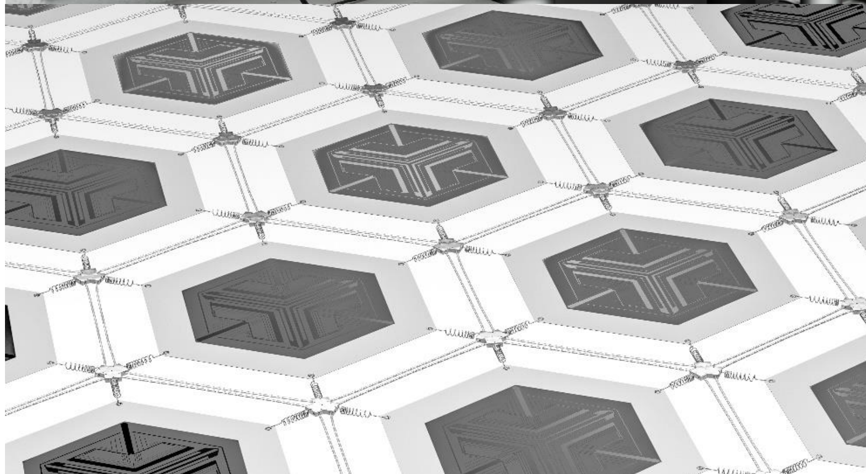
SAES® is an **advanced functional materials** Group, focusing its business on the development and production of proprietary and specifically engineered solution (components and systems) for many industrial and scientific applications.

- **Getters components and pumps** to guarantee high and Ultra-High Vacuum conditions in a variety of applications such as :
  - > Particle Accelerators and High Energy Labs
  - > Analytical Instrumentation
  - > Processing Tools for semiconductor
  - > Vacuum Systems
  - > Consumer electronics

- **Shape memory components and systems** like SMA wires , springs, actuators and valves for consumer electronics, automotive and white goods industries

- **Functional composites and coated films** to protect goods for the packaging industry





SAES Group worldwide coverage

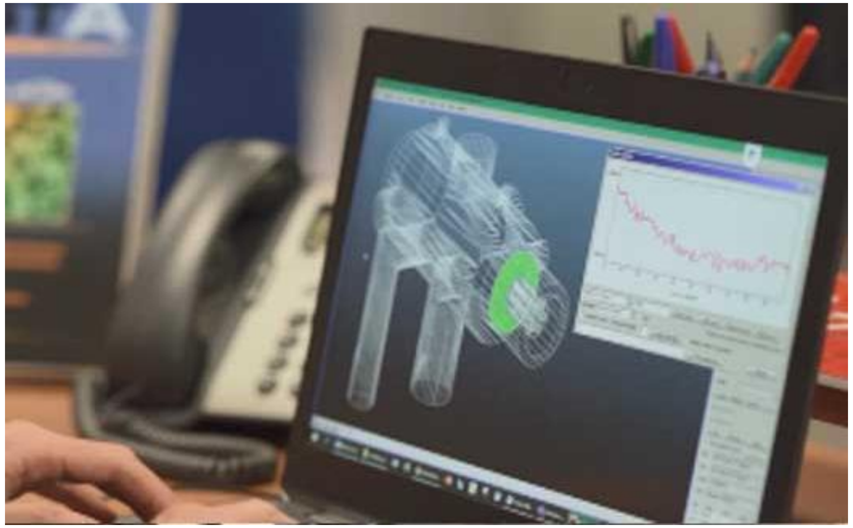
High Vacuum Division facilities:

- HQ in Milano;
- SRV in Parma;
- CINEL in Padova;
- SAES Getters (NEG pumps) in Avezzano

Our Research and Innovation

A high percentage of revenues (7-10%) allocated to R&D every year

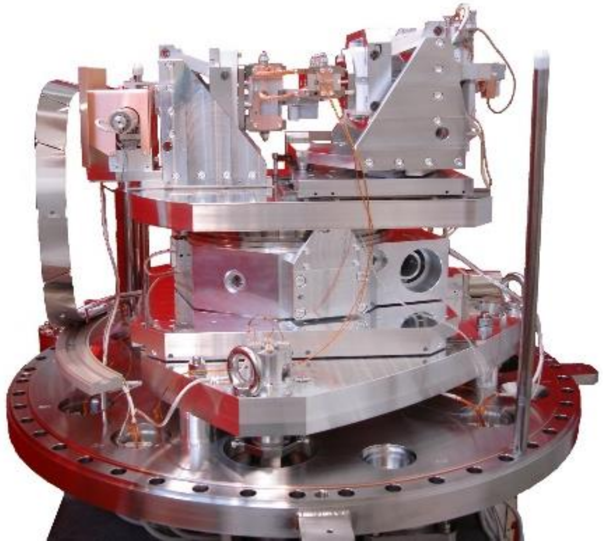
- State-of-the-art corporate laboratories covering a surface of over 3,300 sqm
- More than 150 highly skilled people engaged in R&D activities world-wide. Almost 17% of the total workforce of the Group, about 50% are graduated (mainly in Physics, Chemistry, Engineering and Material Science) -> 20% of graduated are PhD
- 233 Scientific Papers and Conference Proceeding published in the last 20 years
- Strong cooperation with Universities and R&D centers.



High Vacuum Division: 3 pillars

- 1970-2024 : Pumps and getter solutions per high and ultra-high vacuum for accelerators, synchrotrons, research and industry.
- 2015: Vacuum chambers and components for the synchrotron ring through **SAES RIAL Vacuum** (Parma)
- 2021: vacuum chambers, monochromators, mirror systems, front end, beamlines and scientific instrumentations for synchrotrons through **Strumenti Scientifici Cinel** (Vigonza).

With 4 manufacturing sites (Parma, Vigonza, Lainate, Avezzano) and 100 headcounts, the High Vacuum Division is well positioned to provide integrated solutions to new accelerator facilities.



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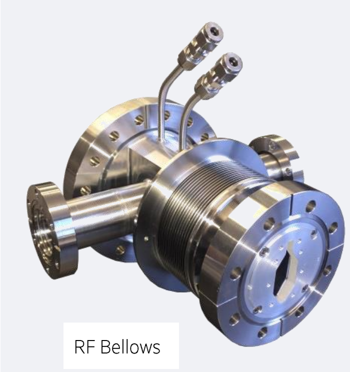
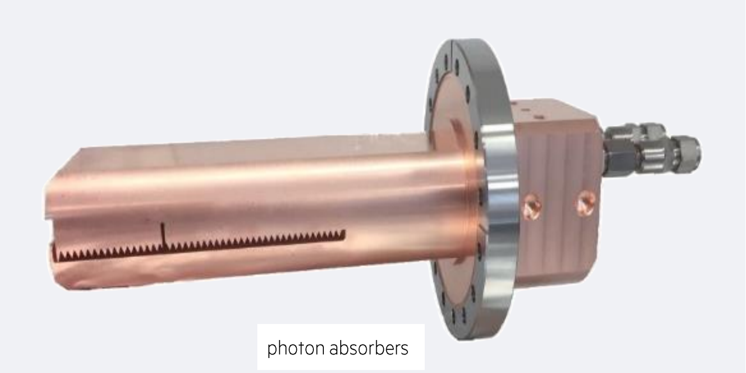
The role of SAES®, SRV and Cinel

- **Even though formally independent** the three companies are actually working in close cooperation with each other
- They do share equipment and provide each other with the following services:
    - **SAES®** provides NEG coating, broad R&D support, analytical services, mathematical/physical tools
    - **SRV**: cleaning services, welding technologies, metrological testing
    - **Cinel**: EDM machining, brazing, CNC machining, metrology
- This allows to
    - Significantly increase the amount of technical competences and expertize within the Division
    - Increase type and number of equipment and their availability
    - Increase overall manufacturing capacity and throughput

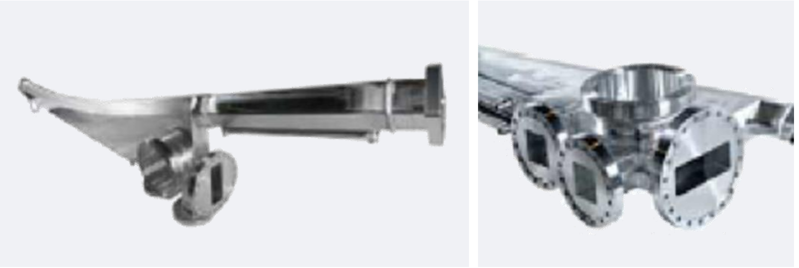


RF Bellows

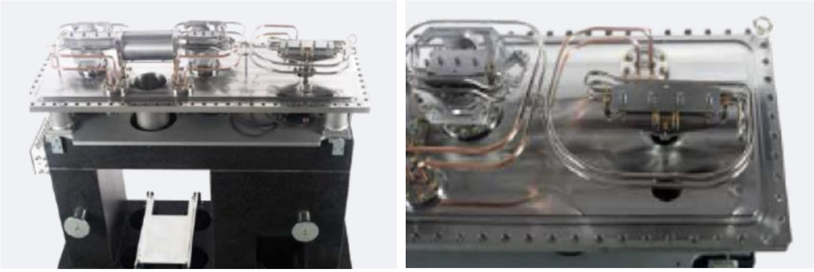


photon absorbers

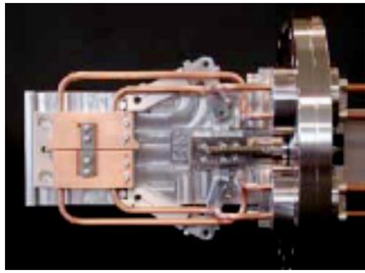
Mirror chamber for Protein Cristallography Beamline (M1)
X0oDA Swiss Light Source SLS Villigen (Switzerland)



Vacuum Chamber
Elettra Synchrotron Laboratory Trieste (Italy)



Mirror chamber for X-ray Deimos Beamline
Synchrotron Soleil Saint-Aubin (France)

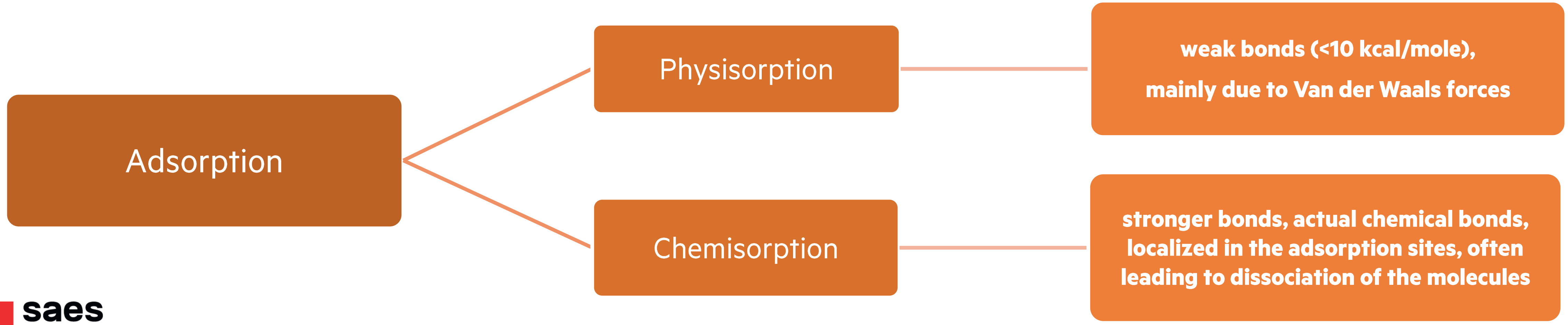


High Precision Water Cooled Slit
Canadian Light Source-CLC
Saskatchewan University (Canada)

WHAT IS A NON-EVAPORABLE GETTER (NEG): main chemico-physical properties

Main characteristics of a getter

- Getters are solid materials able to **pump chemically-active gases** (H_2O, CO, CO_2, O_2, N_2) through the formation of stable chemical bounds on their surface
- This reaction generates chemical compounds (carbides, nitrides, oxides) on the getter surface: gases are **permanently** removed from the vacuum system
- Unlike other gases, **hydrogen** cannot react and produce chemical compounds, but it **can diffuse inside the bulk**, where it forms a solid solution
- Due to their nature, **noble gases cannot react** with a getter surface. **Methane also cannot be pumped** by a getter
- To be able to provide adsorption on its surface, a getter should have an **active surface layer** with free sites available to form bonds with gas molecules; by adsorbing particles on its surface the number of vacant sites decreases, until a reactivation of the material becomes necessary



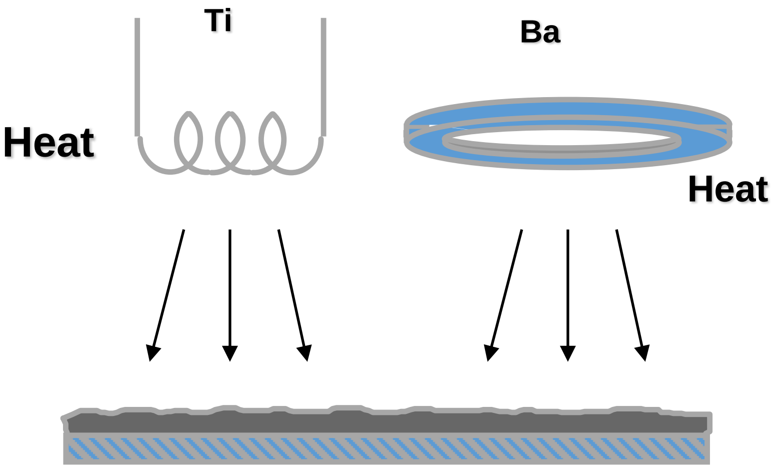
Families of getters

Getters can be of two types, according to the method adopted to achieve their activation:

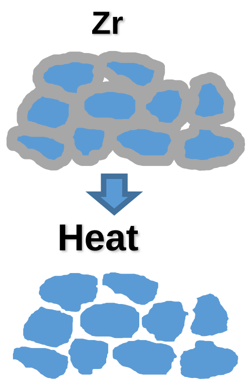
> ***evaporable getters*** are obtained by in-vacuum **sublimation and deposition** of a fresh getter film on a metallic surface;

> the active surface of a ***non-evaporable getter* (NEG)** is obtained by **thermal diffusion** of the surface oxide layer, which contains adsorbed gas molecules, into the bulk of the material itself.

Evaporable Ca, Sr, **Ba**, Ti*	Non-evaporable Ti*, **Zr**, Th



Evaporation → TSP

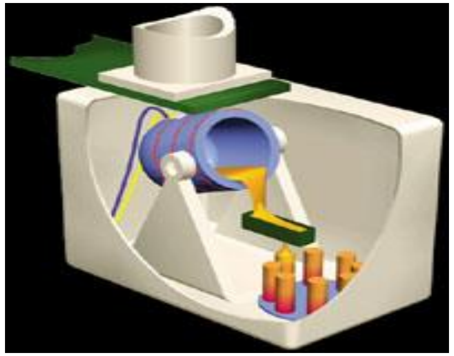


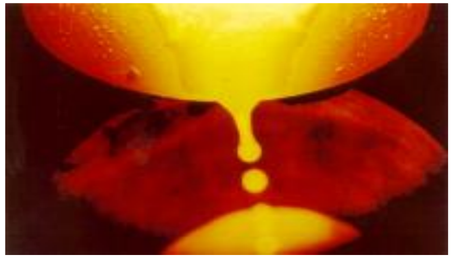
Active getter material

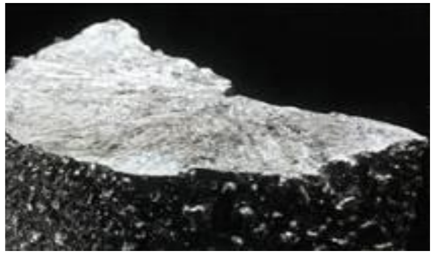
Activation → NEG

GETTER MANUFACTURING PROCESS

Alloy Ingot preparation

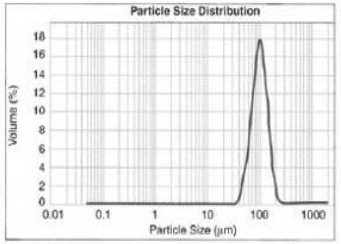




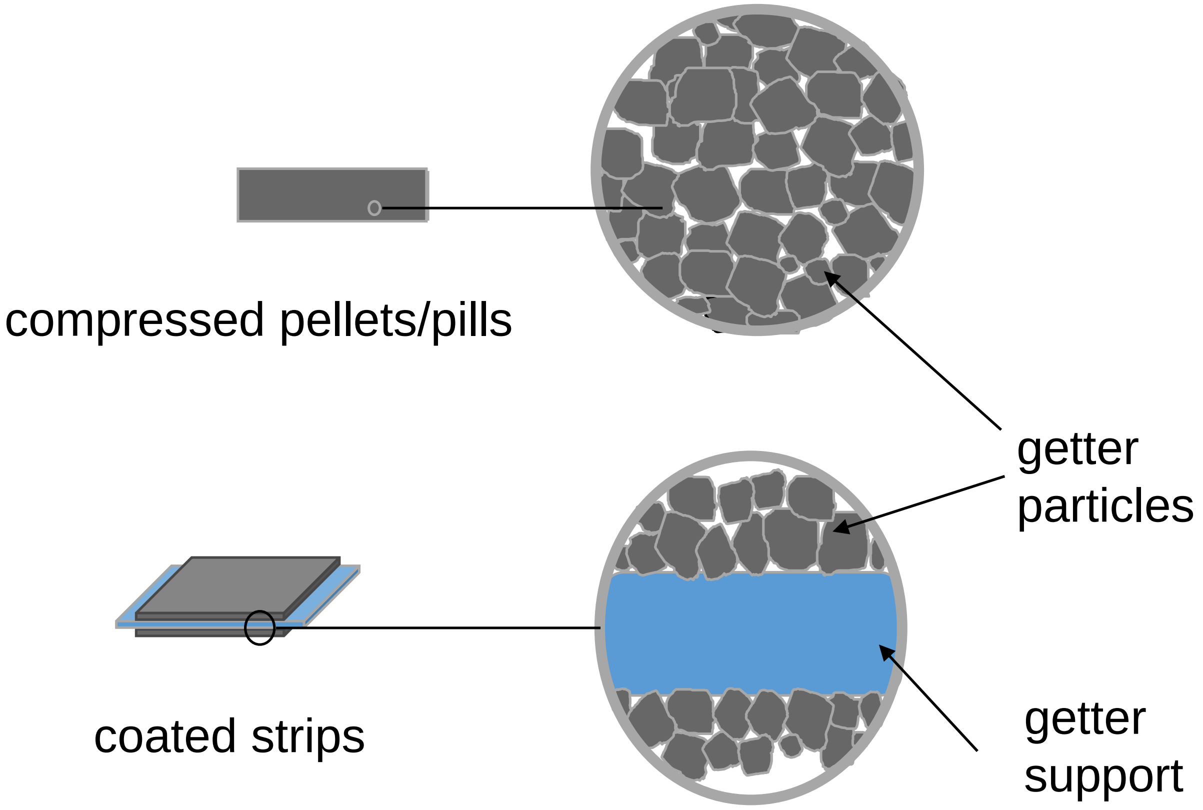


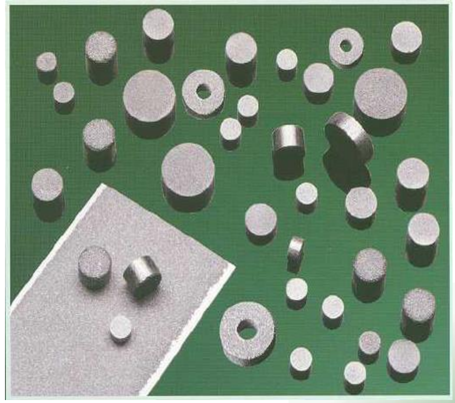
Alloy Ingots Grinding → Alloy Powder Sieving & Mixing → Getter Forming & Shaping

- Cold lamination
- Compression
- Sintering



COMPRESSED GETTER CONFIGURATIONS

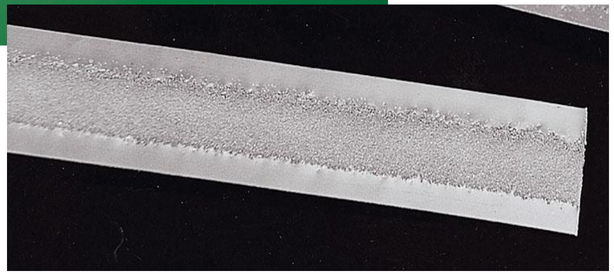




PILLS, TABLETS, RINGS

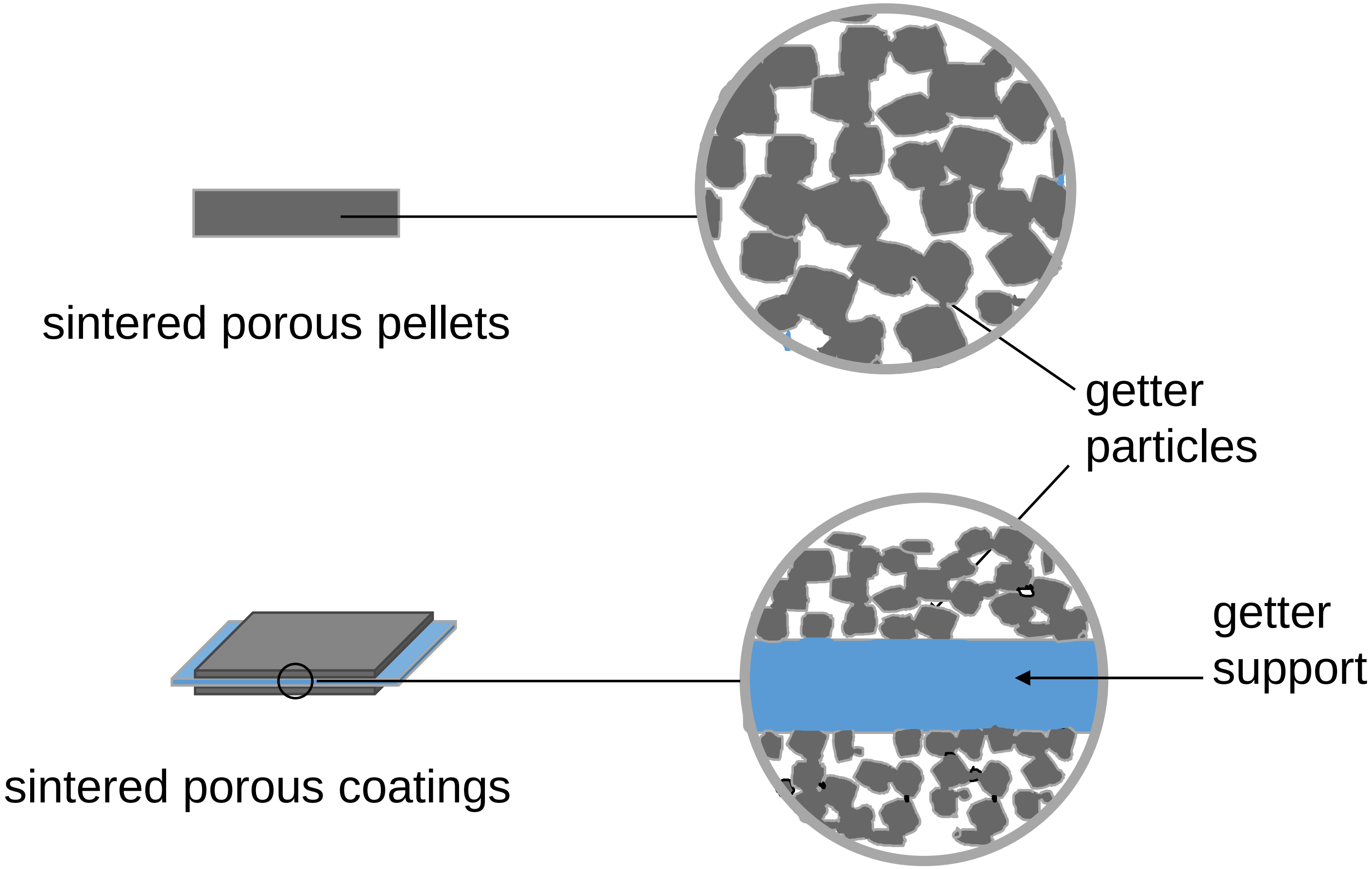
MODULES

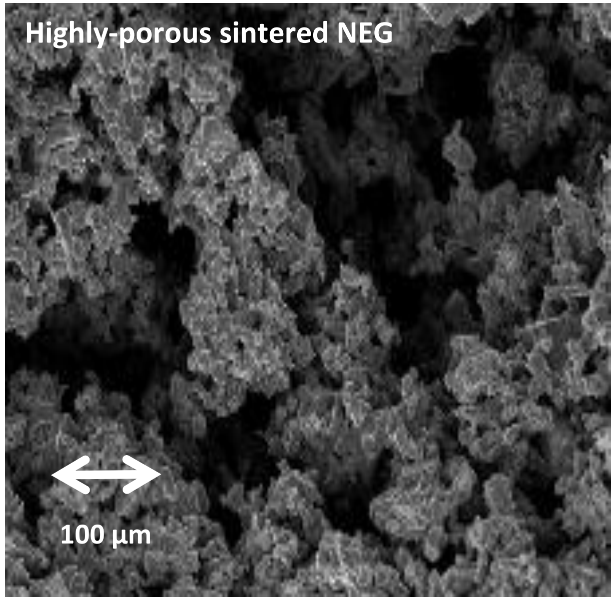
COATED STRIP



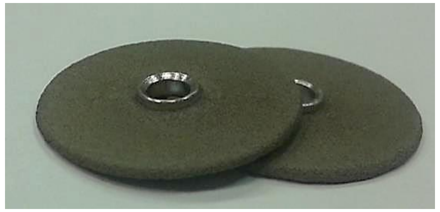
SINTERED GETTER CONFIGURATIONS

Sintering is a high-temperature process carried out in high vacuum. During sintering, adjacent grains bond together by surface melting, creating a **single network** not prone to release particles.





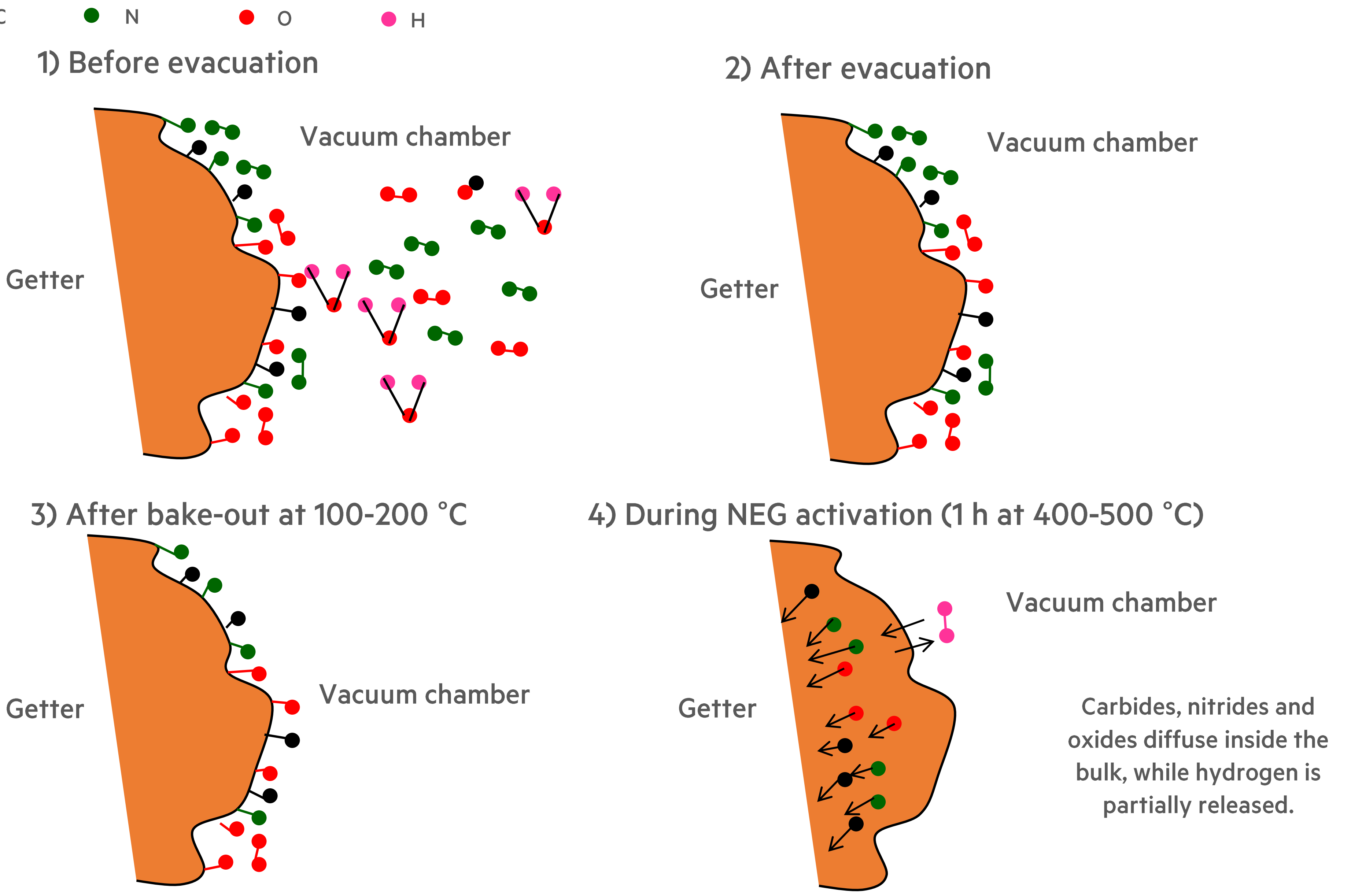
Large porosity
=
High conductance
=
Large sorption speed



PRINCIPLES OF NEG OPERATION

- NEGs need to be heated under vacuum: ACTIVATION
    - Moderate activation temperature : 400–500 °C
    - Short time: ≈ 60 min
- After activation, the pump sorbs 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).

NEG activation and sorption mechanisms



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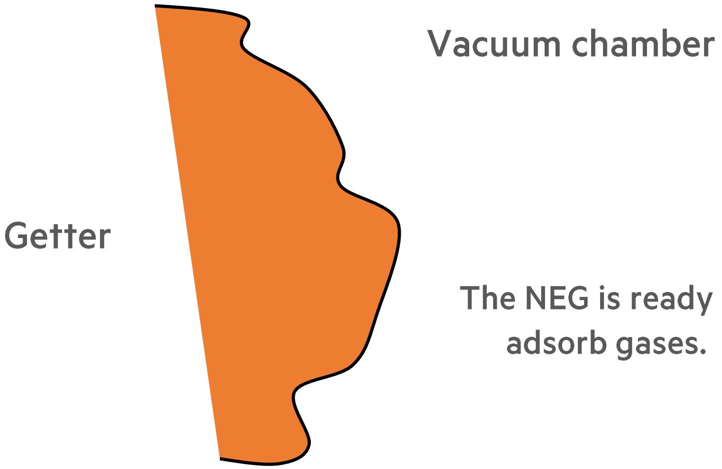
NEG activation and sorption mechanisms

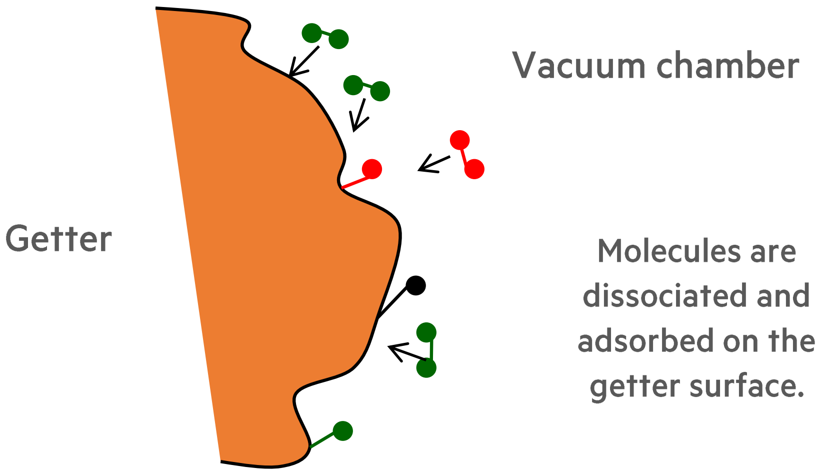
● C ● N ● O ● H

5) After NEG activation



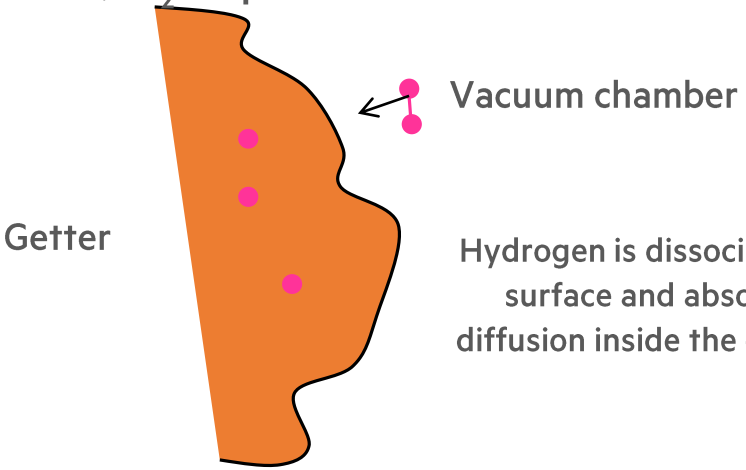
The NEG is ready to adsorb gases.

6) H_2O, CO, CO_2, N_2, and O_2 sorption mechanism



Molecules are dissociated and adsorbed on the getter surface.

7) H_2 sorption mechanism



Hydrogen is dissociated on the surface and absorbed by diffusion inside the getter bulk.

Following saturation, a getter can be reactivated more than 100 times throughout its lifetime!

NEG ACTIVATION PROCESS

Activation:

- Diffusion of surface protective layer

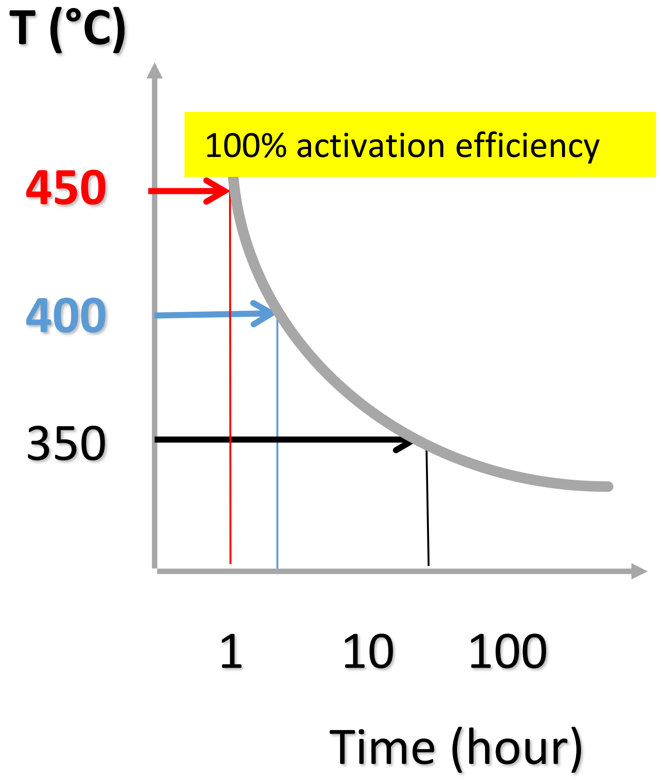
Diffusion phenomena:

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

In some situations it is not possible to achieve 100% activation efficiency due to time or temperature constraints.
A "partial" activation can however be sufficient in some cases.



Why NEGs are so effective for H_2: Sieverts' law

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:

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

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

The process is reversible: H_2 is preferentially sorbed or emitted depending on temperature.

At RT, estimated H_2 eq. pressure of St172™ is **<10^{-15} mbar**.
The getter is a perfect **sink** for H_2.

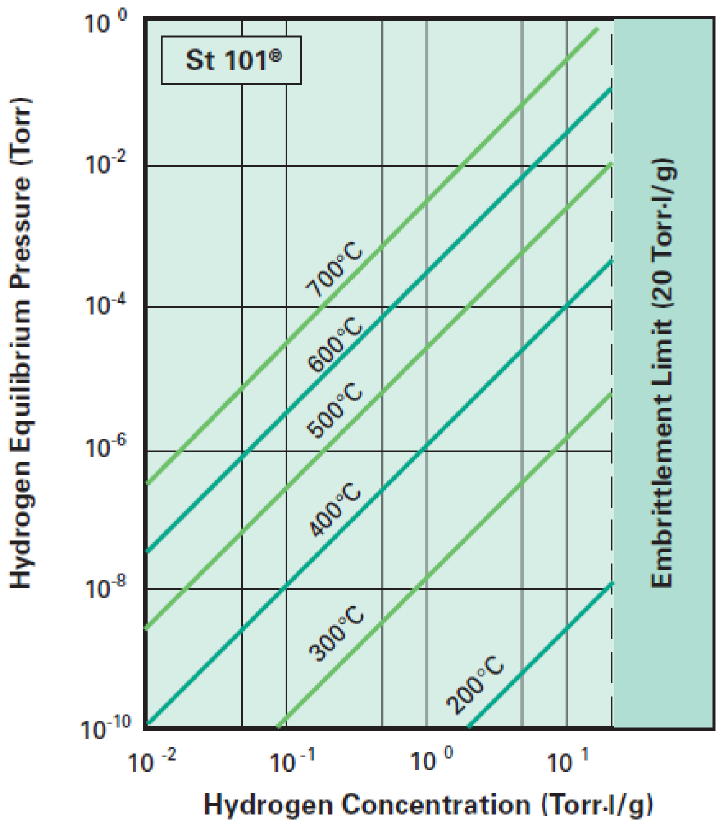
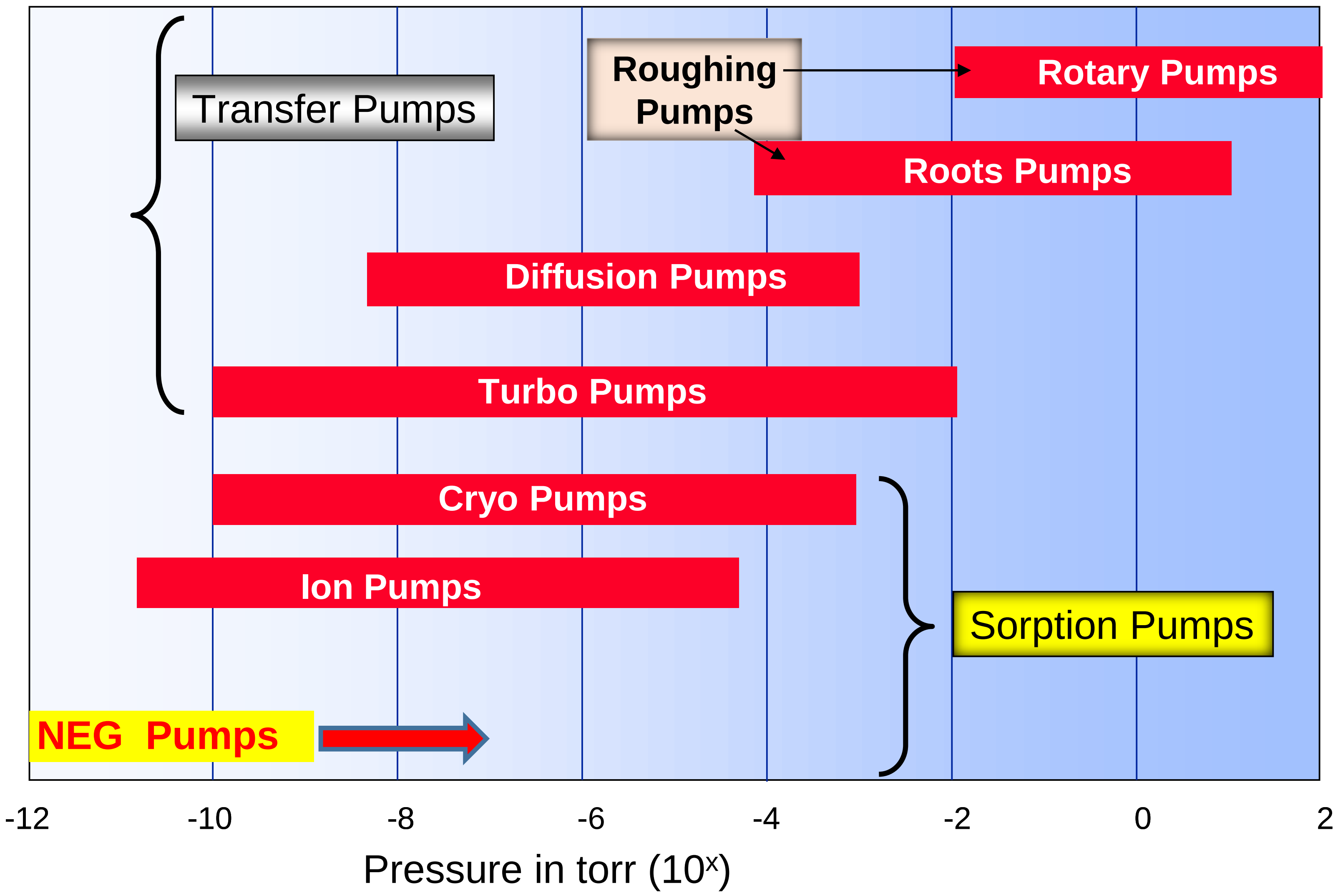


Figure 3 - Hydrogen Equilibrium Pressures of St 101 Alloy

NEG PUMPS: key features

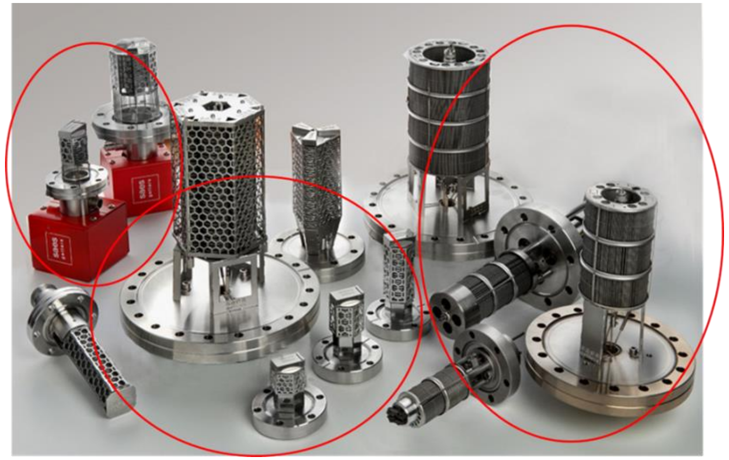
Pressure ranges of vacuum pumps



From NEG to NEG pumps: key features

NEG pumps are extremely suitable for UHV applications as they provide :

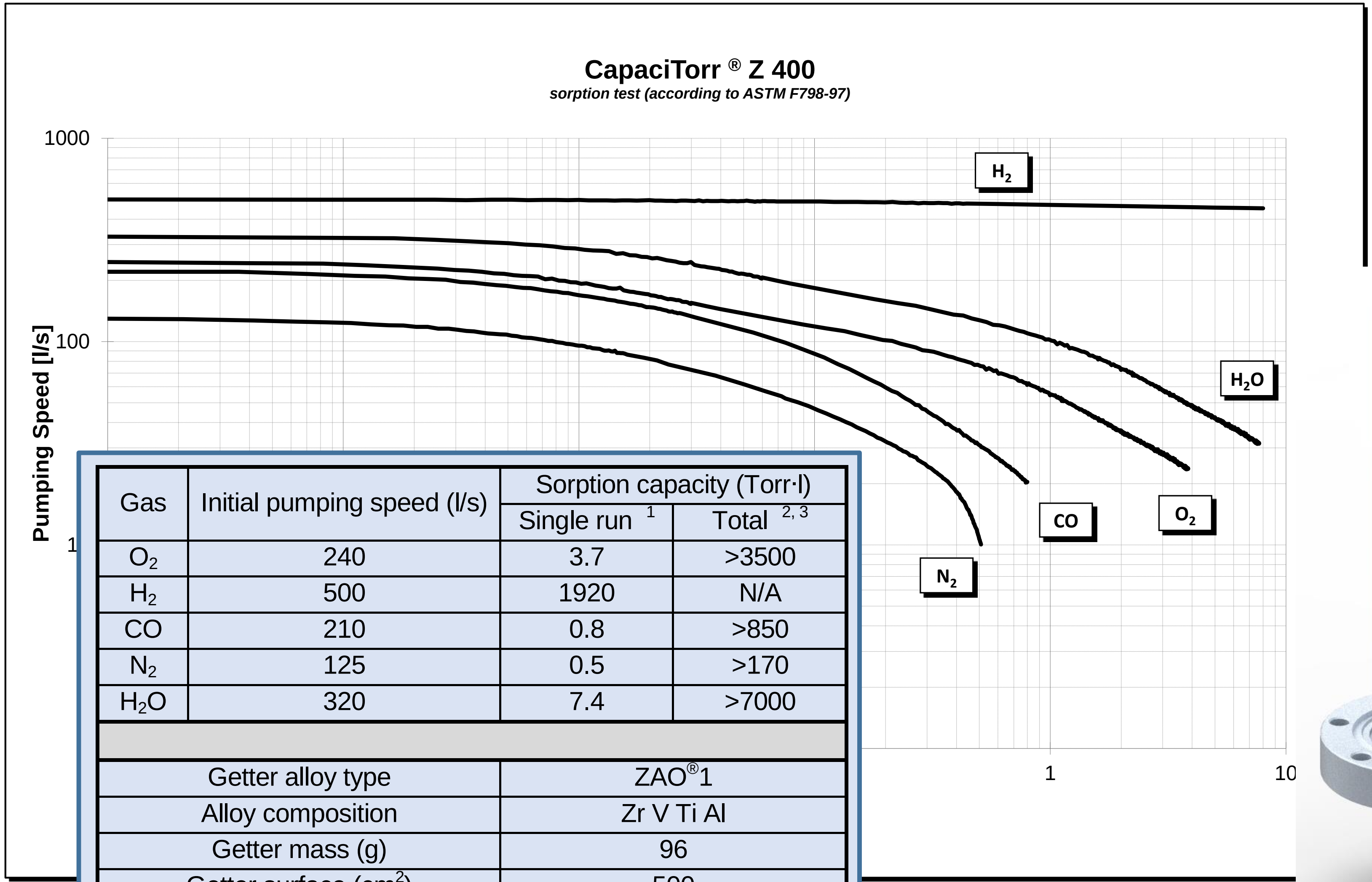
- very large pumping speed -> better vacuum level
- compact and light package -> miniaturization and compactness
- high trapping efficiency for H_2 (they main UHV-XHV residual gas)
- powerless operation
- vibration free operation
- reliability in case of power outage as vacuum will be preserved by NEG
- no maintenance
- negligible magnetic interference
- best vacuum on earth (10^{-12} Pa, Benvenuti et al.)



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

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

TYPICAL SORPTION CURVES FOR NEGs



Gas	Initial pumping speed (l/s)	Sorption capacity (Torr·l)	
		Single run [1]	Total [2, 3]
O_2	240	3.7	>3500
H_2	500	1920	N/A
CO	210	0.8	>850
N_2	125	0.5	>170
H_2O	320	7.4	>7000

Getter alloy type	ZAO®1
Alloy composition	Zr V Ti Al
Getter mass (g)	96
Getter surface (cm^2)	500

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NEG PUMPS OVERVIEW: from alloys to main models

NEG ALLOYS AND PUMPS OVERVIEW

St707® compressed

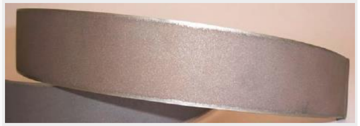
St172™ sintered

ZAO® UHV and HV sintered

NEG pumps

1960 1970 1980 1990 2010 2015

Laminated St707 ®strip



Wafer modules

Wafer modules
300 to 900 l/s for H_2

GP cartridges:
200 to 2000 l/s for H_2

Porous sintered disks

CapaciTorr® series:
50 to 3600 l/s for H_2

ZAO® porous sintered disks

NEG pumps extended from UHV to HV

Negligible particle emission
Ultra-low degassing
Increased pumping speed

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

ZAO® pumps for HV and UHV applications

MEGA ZAO® pump for Fusion Energy

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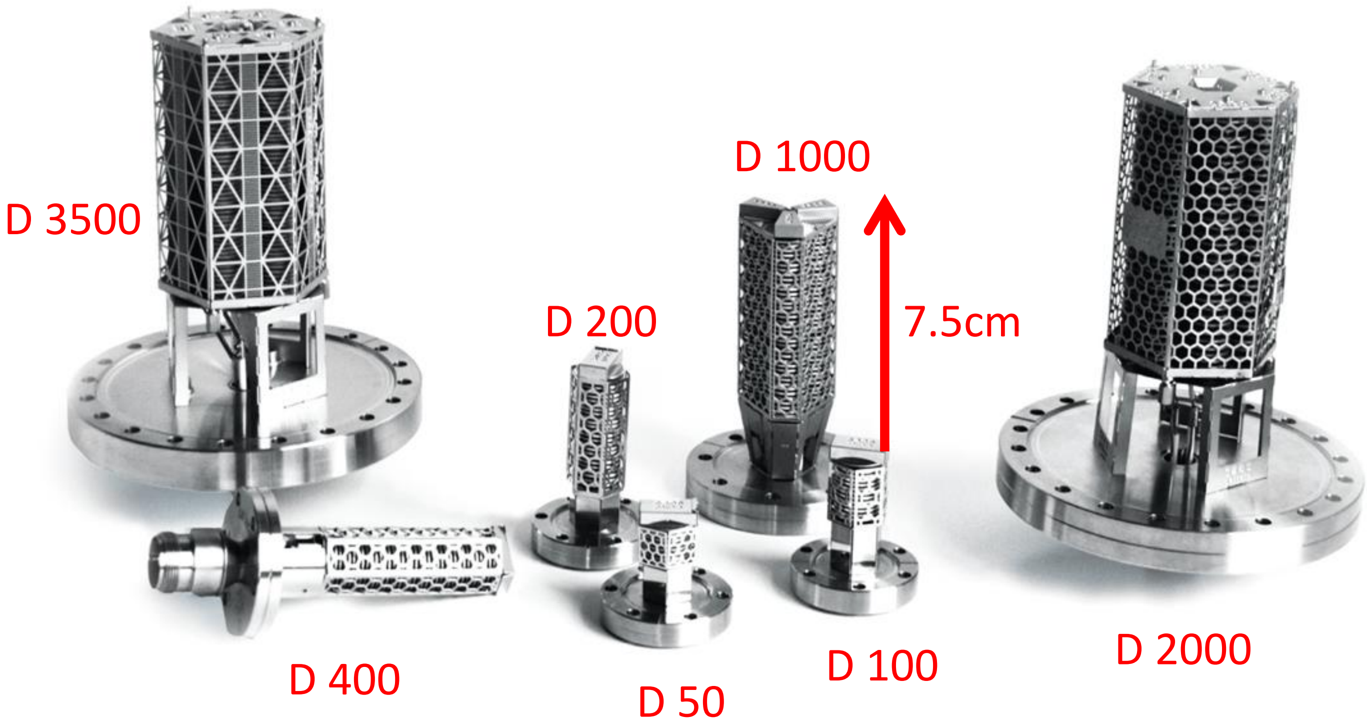
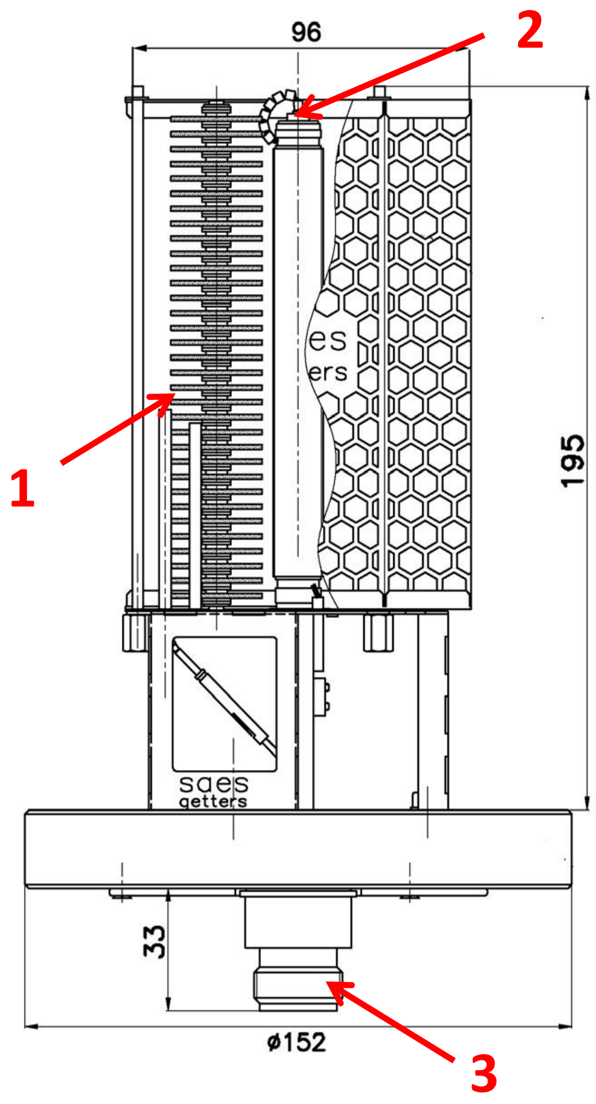
The CapaciTorr® family: D NEG pumps

- Made of sintered, highly-porous St172™ NEG disks, which ensure high pumping speeds and sorption capacity in a small space.
- 7 models are available, with H_2 pumping speeds ranging between 50 l/s and 3500 l/s.



The CapaciTorr® family: characteristics

- very compact and light weight
- no vibrations
- no need for electric power, except during activation
- no magnetic interference
- work in UHV conditions



CapaciTorr® D2000 :

1. NEG disks
2. Heater
3. Electrical feedthrough

ZAO®: another family of NEG materials

ZAO®, a relatively new (2014) alloy, made of Zr-V-Ti-Al, has got the following advantages:

- a **lower hydrogen equilibrium pressure**, even at high temperature;
- a **larger capacity** for every active gas;
- the ability to undergo **several reactivation cycles**, without compromising the performance of the material;
- **better mechanical properties**: disks are intrinsically more resistant, also from the H_2 embrittlement point of view.

ZAO® UHV disks

- high pumping speed for H_2 and all active gases
- strong mechanical properties
- extremely low particle emission

ZAO® HV disks

- ability to pump large gas quantities
- ability to work at ~200 °C
- strong mechanical properties
- extremely low particle emission

The CapaciTorr® family: Z NEG pumps

These UHV pumps are made of sintered, highly-porous ZAO® NEG disks, which ensure:

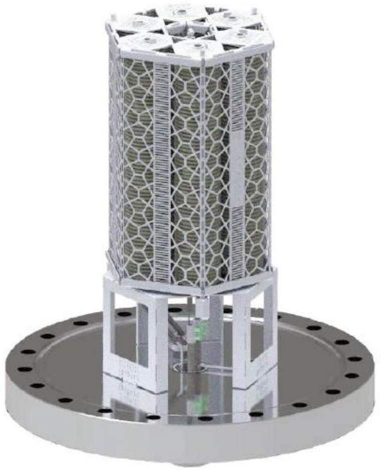
- lower particulate emission than St172™ disks
- higher pumping speed for hydrogen

Z 100

Z 200

Z 400

Z 1000



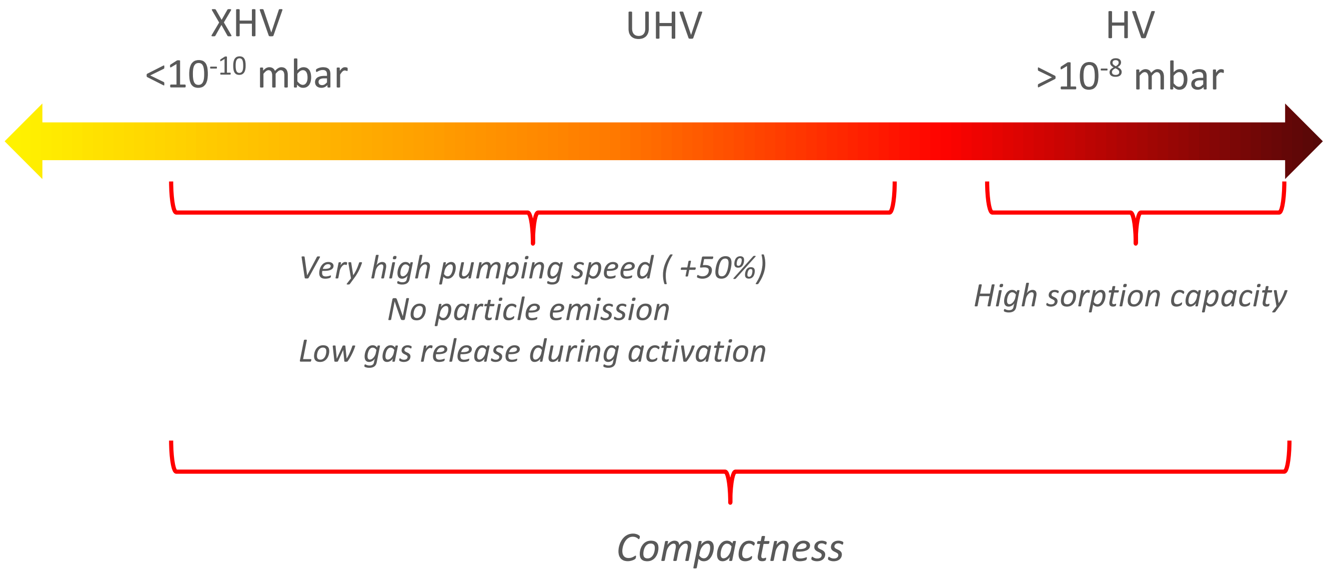
Z 3500

High Vacuum applications

Lots of vacuum systems operate in HV:

- **Analytical equipment** : mass spectrometers, gas analyzers, focused ion beam systems…
- **Medical accelerators** for cancer therapy, cyclotrons and a variety of industrial accelerators used for material irradiation and surface engineering
- **High-energy physics accelerators** (e.g., some FELs, LINACs, boosters, neutron spallation sources, Beam lines) or large physics experiments (e.g., VIRGO for gravitational waves)
- **Semiconductor processing equipment** (PVD, CVD, ion implantation…)

- One of the main limitations of NEG pumps working at RT 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)



NEG pumps in UHV vs HV

CapaciTorr® D 400

☐ Gas to sorb : CO **at 10^{-10} mbar**

- Average pumping speed : 100 l/s
- Pump capacity (CO) : 1,2 mbar l
- CO sorbed in 1 year: 100l/s*10^{-10}mbar*(365*24*3600s)=0,37 mbar l
- Time between reactivations: 1,2 mbarl/0,37 mbar l = **1100 days (≈3 years)!!**

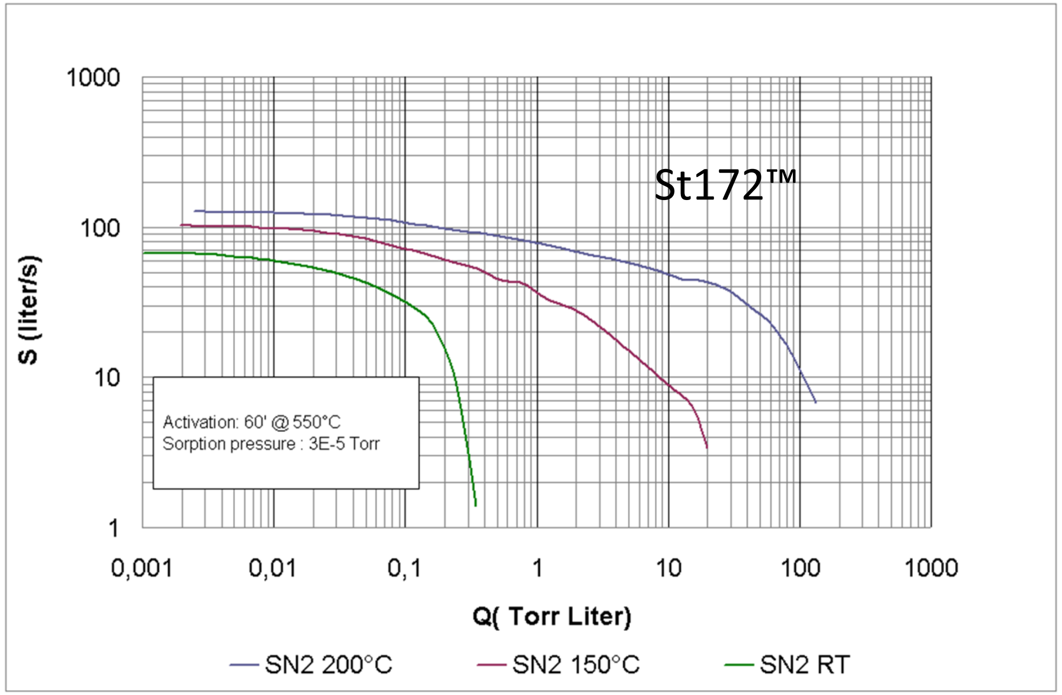
☐ Gas to sorb : CO **at 10^{-8} mbar**

- Average pumping speed : 100 l/s
- Pump capacity (CO) : 1,2 mbar l
- CO sorbed in 1 year: 100l/s*10^{-8}mbar*(365*24*3600s)=37 mbar l
- Time between reactivations: 1,2 mbar l/37 mbar l = **11 days!**

Conclusions: even considering the most difficult gas to sorb (CO), under UHV conditions, SAES® CapaciTorr® pumps based on St172™ can operate for years before needing reactivation. They would require frequent activations at 10^{-8} mbar.

ZAO® HV pumps

- It is known that the capacity of NEGs increases with temperature. Temperature activates diffusion of carbides, oxides etc., so that it takes much longer than at RT to saturate superficial adsorption sites.
- However, for St172™:
  - ➢ H_2 eq. pressure at 200 °C is too high → **ineffective pumping of H_2O and H_2**
  - ➢ Pumping performances decay after few sorption cycles at high pressure → **short-lived pump**

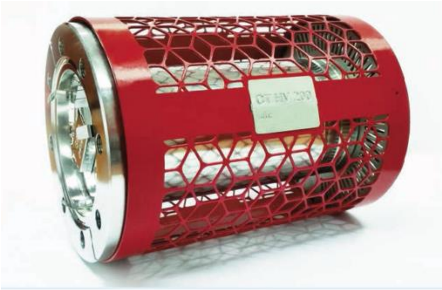


ZAO® HV alloy is the solution for HV applications, providing, among main benefits of ZAO® alloy:

- lower equilibrium pressure
- ability to sorb large gas quantities

The CapaciTorr® HV pumps

- Capacitorr® HV pumps are based on the ZAO® alloy
- Starting from 1E-2mbar in pump-down
- Down to 1E-7mbar (or even lower pressure)
- Very large pumping speed for getterable gases
- Very large capacity
  - Work at 1E-8 mbar of CO or N_2 for more than 1 year without reactivation
  - Work at 5E-8 mbar of H_2O for more than one year without reactivation
- Operation at Moderate temperature (180-200°C)
- Ability to pump at room temperature for a limited time
- NEG material with the lowest particulate release



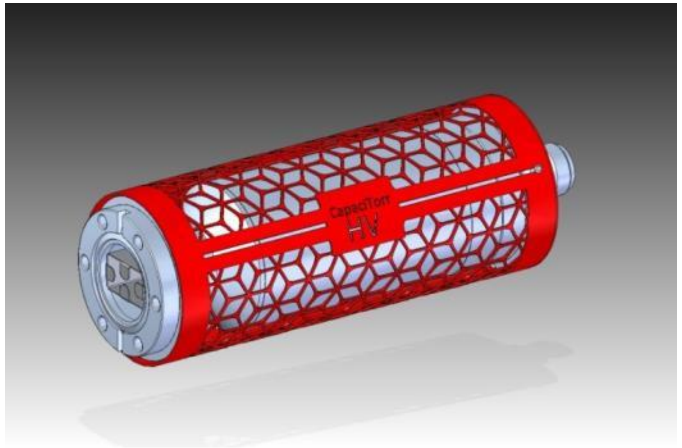
CapaciTorr® HV200

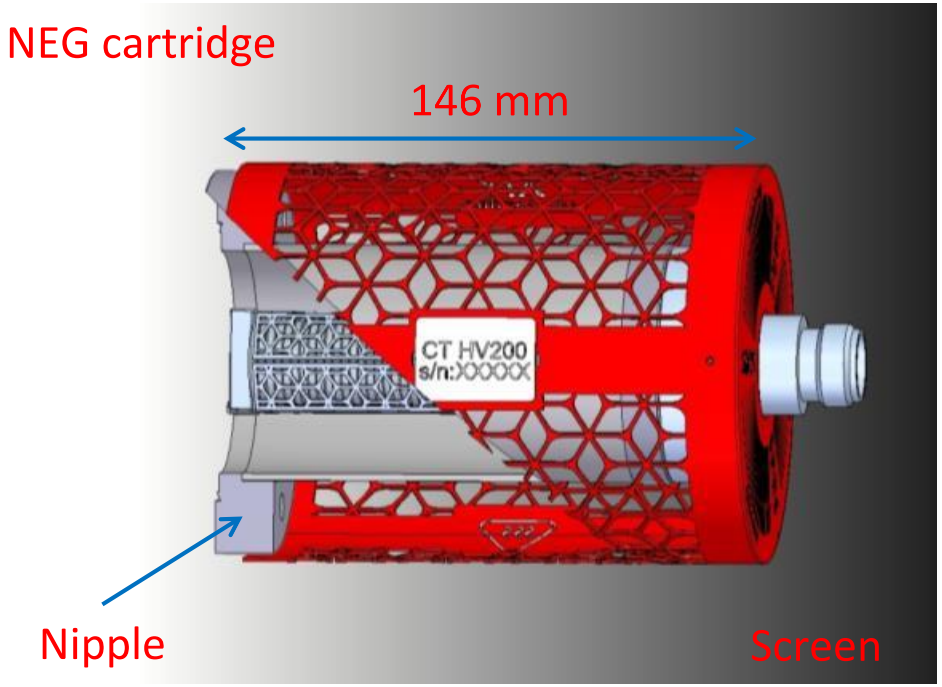
CapaciTorr® HV2100

CapaciTorr® HV1600

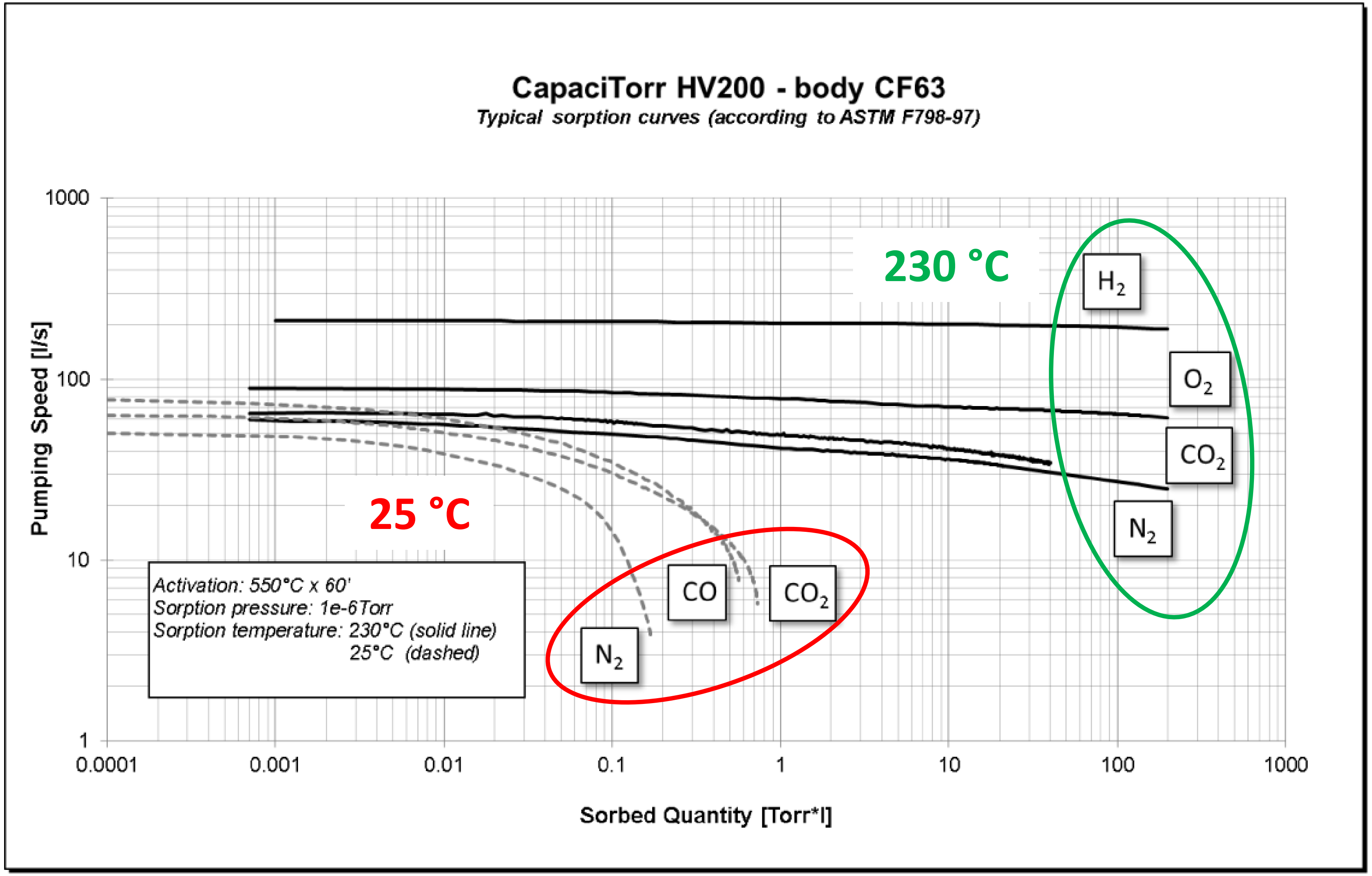
An example of ZAO®-based HV pump: CapaciTorr® HV 200

- Pump placed inside a nipple, which allows a more efficient thermal management
- Available on CF35 or CF63
- 8 W necessary to keep the pump at ~200 °C
- Initial H_2 pumping speed: 210 l/s
- Can work in the 10^{-8} Torr range for 1 year
- At least 20 sorption-reactivation cycles are possible

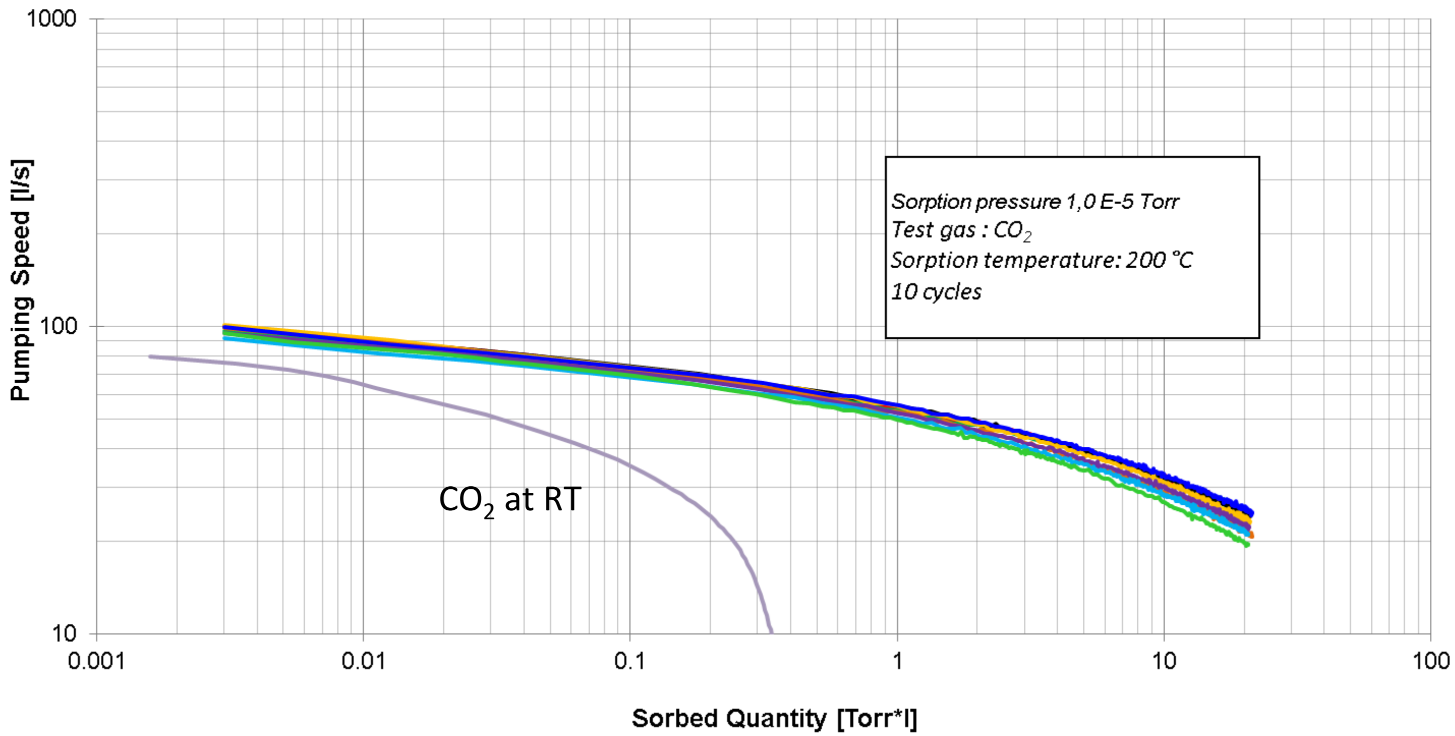




CapaciTorr® HV 200



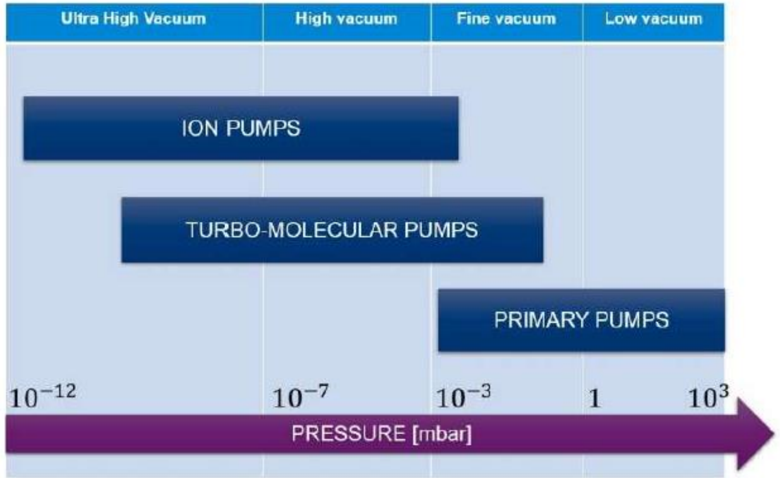
CapaciTorr® HV 200



- Series of 10 accelerated pumping tests at 200 °C at 10^{-5} Torr (CO_2)
- After each reactivation, the performances decay is very small

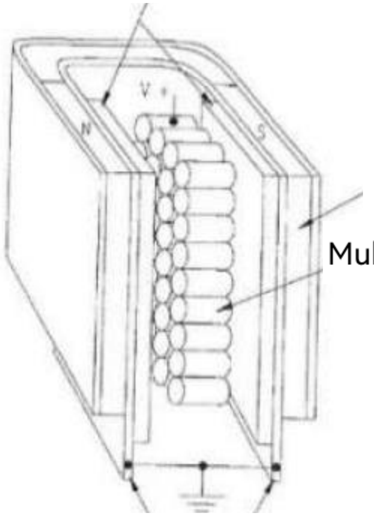
INTRODUCTION TO SPUTTER ION PUMPS (SIPs): working principles

SPUTTER ION PUMPS: structure



- **Element**: one or more Penning cells, by which gas is pumped. Standard Diode is made of cylindrical cells (anode) and two titanium plates (cathode).
- **Magnets**: axial magnetic field (typical range 1200-1400 G).
- **Feedthrough** used to feed the pump with high voltage (~kV).
- **Inlet flange** to connect the pump and the vacuum chamber.

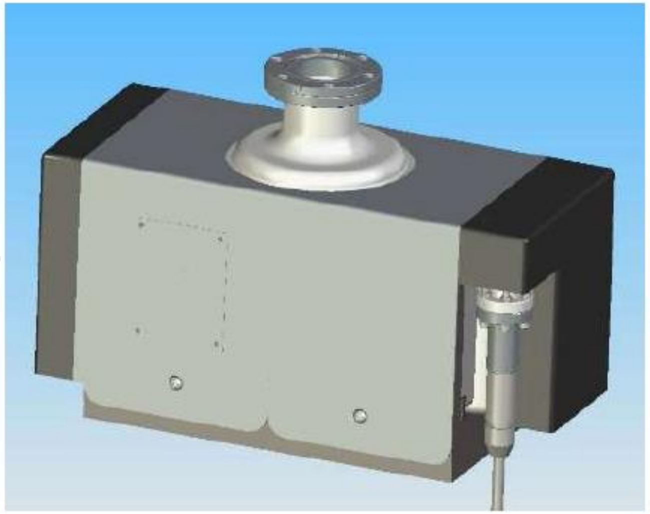
Cathode Titanium



Magnet

Multicell Anode

Pump wall

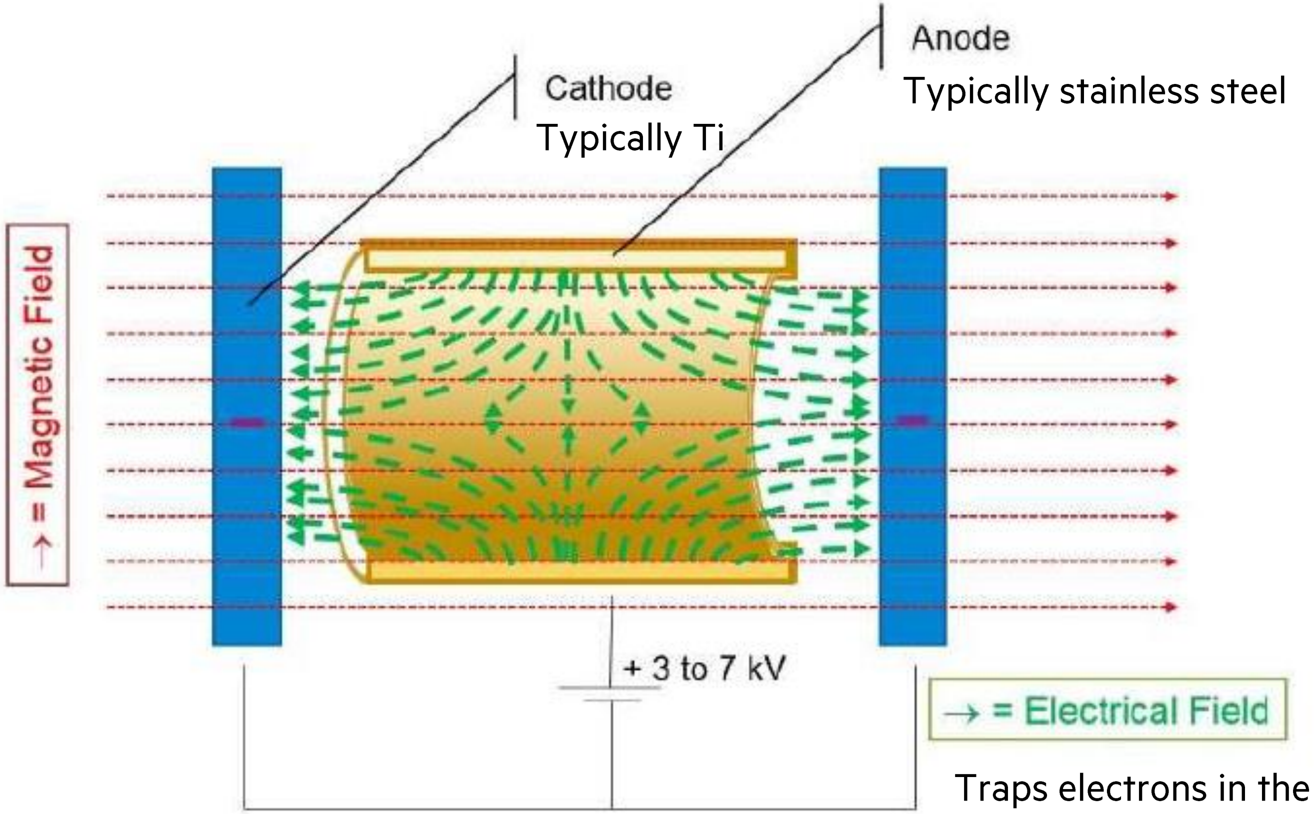


C. Paolini et al., *Ion getter pumps*, Proceeding of the 2017 CERN-Accelerator-School course on Vacuum for Particle Accelerators, Glumslov (Sweden)

SPUTTER ION PUMPS: Penning cell - principles of operation

A high voltage combined with a magnetic field force electrons to travel along a helical path, with an energy sufficient to ionize gas molecules; accelerated ions strike and sputter a cathode plate: titanium atoms are emitted from the cathodes and cover the anode surfaces, creating an active film which chemically traps gas molecules.

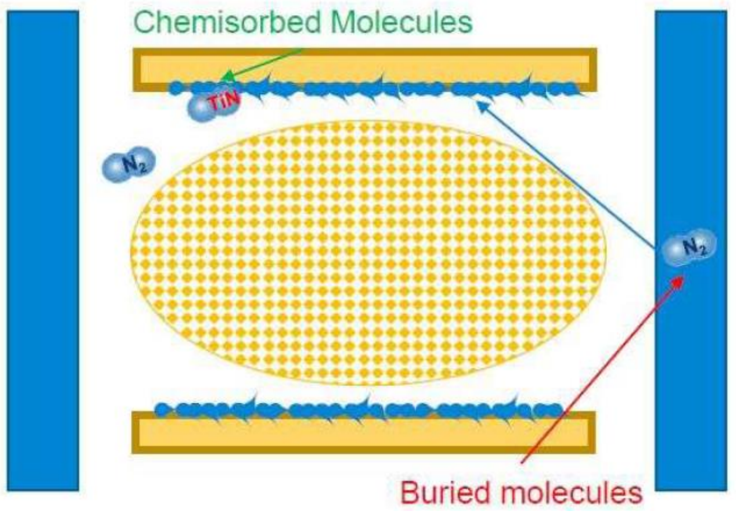
Traps electrons in the radial direction



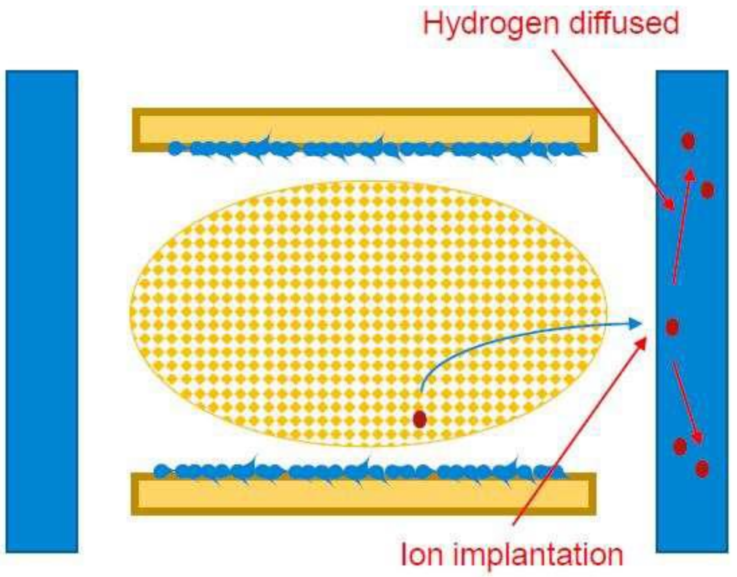
Traps electrons in the axial direction

C. Paolini et al., *Ion getter pumps*, Proceeding of the 2017 CERN-Accelerator-School course on Vacuum for Particle Accelerators, Glumslov (Sweden)

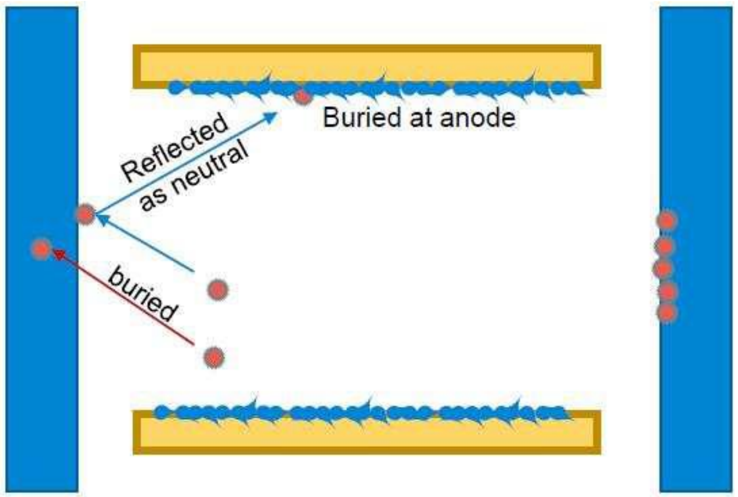
SPUTTER ION PUMPS: pumping mechanisms



Active gases (N_2, O_2, CO, CO_2) chemically combine with sputtered Ti film (some of them might also be neutralized and buried into the titanium cathodes)



Light gases (H_2, He, etc.) are removed by ionization and diffusion into the cathode



Inert gases are removed by ionization and burial at the cathode or reflected as neutrals and buried at the anode

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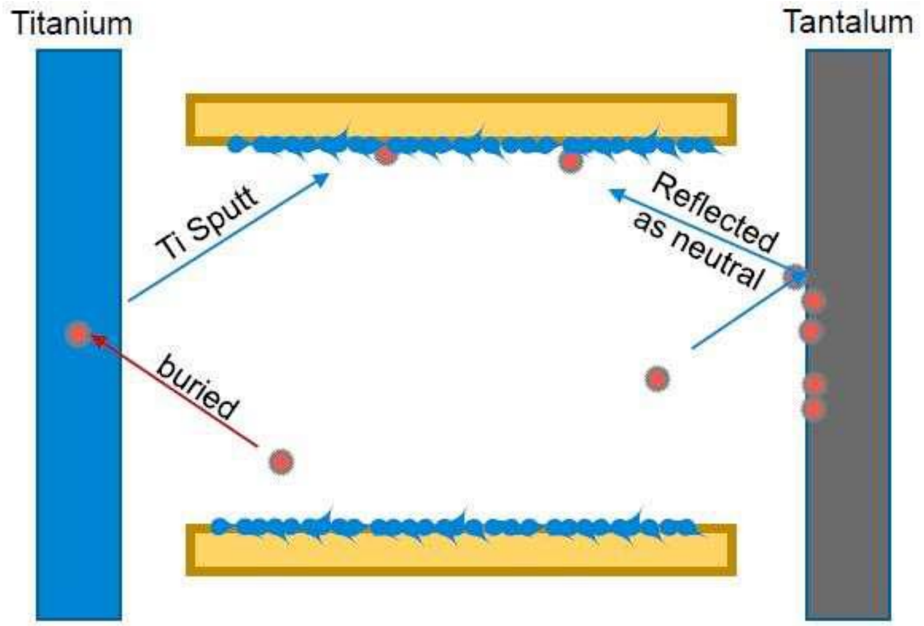
C. Paolini et al., *Ion getter pumps*, Proceeding of the 2017 CERN-Accelerator-School course on Vacuum for Particle Accelerators, Glumslov (Sweden)

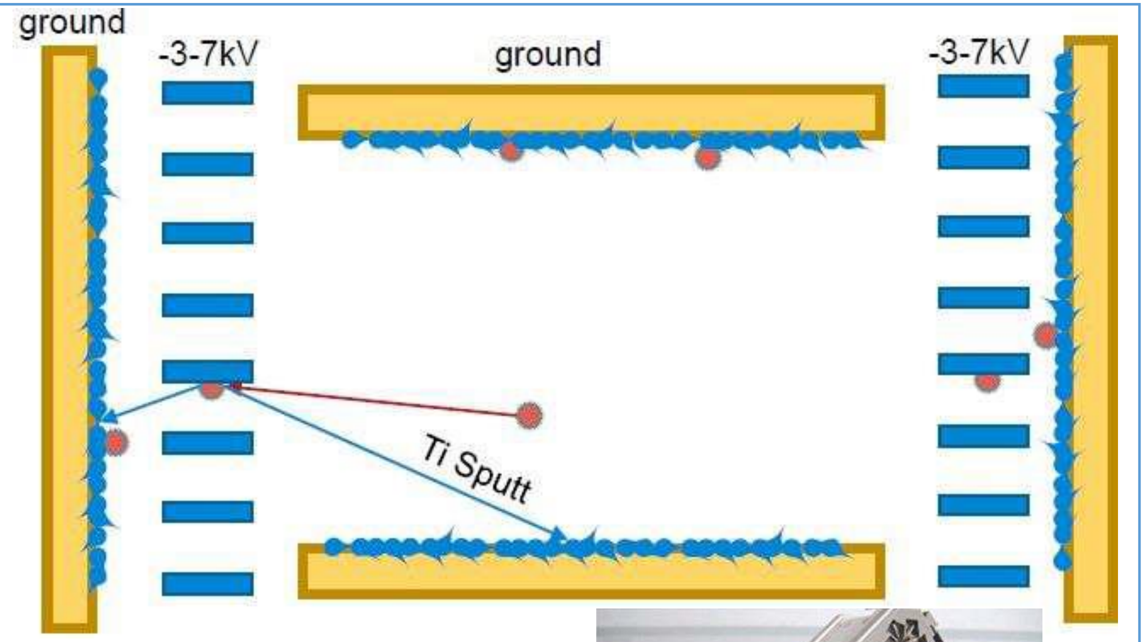
SPUTTER ION PUMPS: different pumping solutions

- Achieving higher pumping speed for noble gases
- Preventing noble gas instability



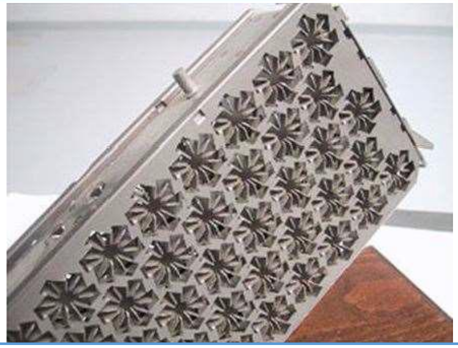
By changing cathode material:

Noble Diode configuration



By changing cathode geometry:

Triode configuration

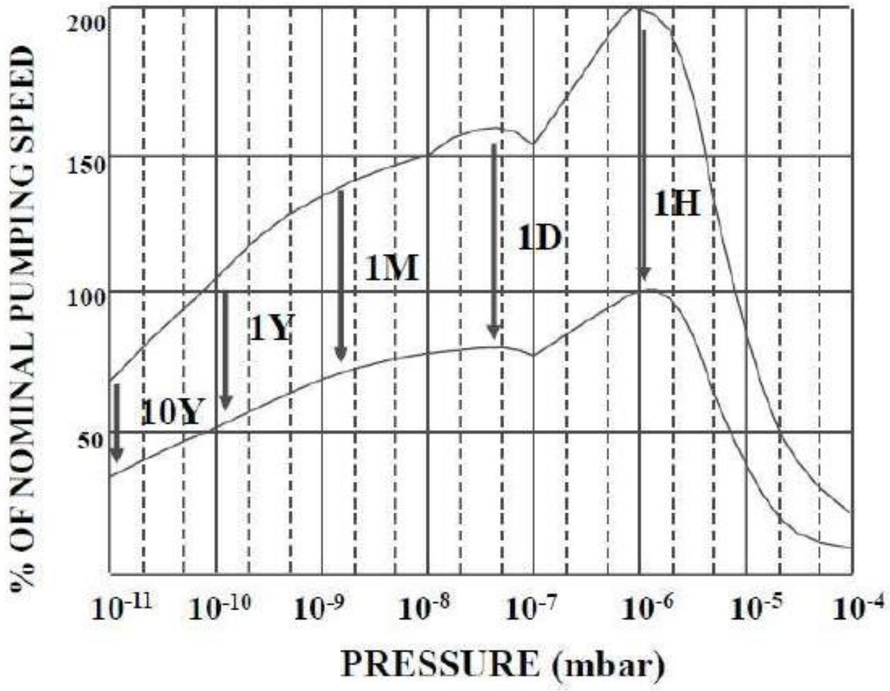


C. Paolini et al., *Ion getter pumps*, Proceeding of the 2017 CERN-Accelerator-School course on Vacuum for Particle Accelerators, Glumslov (Sweden)

SPUTTER ION PUMPS: saturation and leakage current

Saturation concept

As the sputtering of Ti atoms from the cathodes goes on, cathodes are eroded and the previously implanted atoms can be released: net pumping speed decreases until an equilibrium condition between ion implantation and gas re-emission is reached.



Lifetime

- *Erosion* of the cathode along its whole thickness: titanium film cannot be refreshed.
- *Short circuit*: in case of complete metallization of the ceramics.

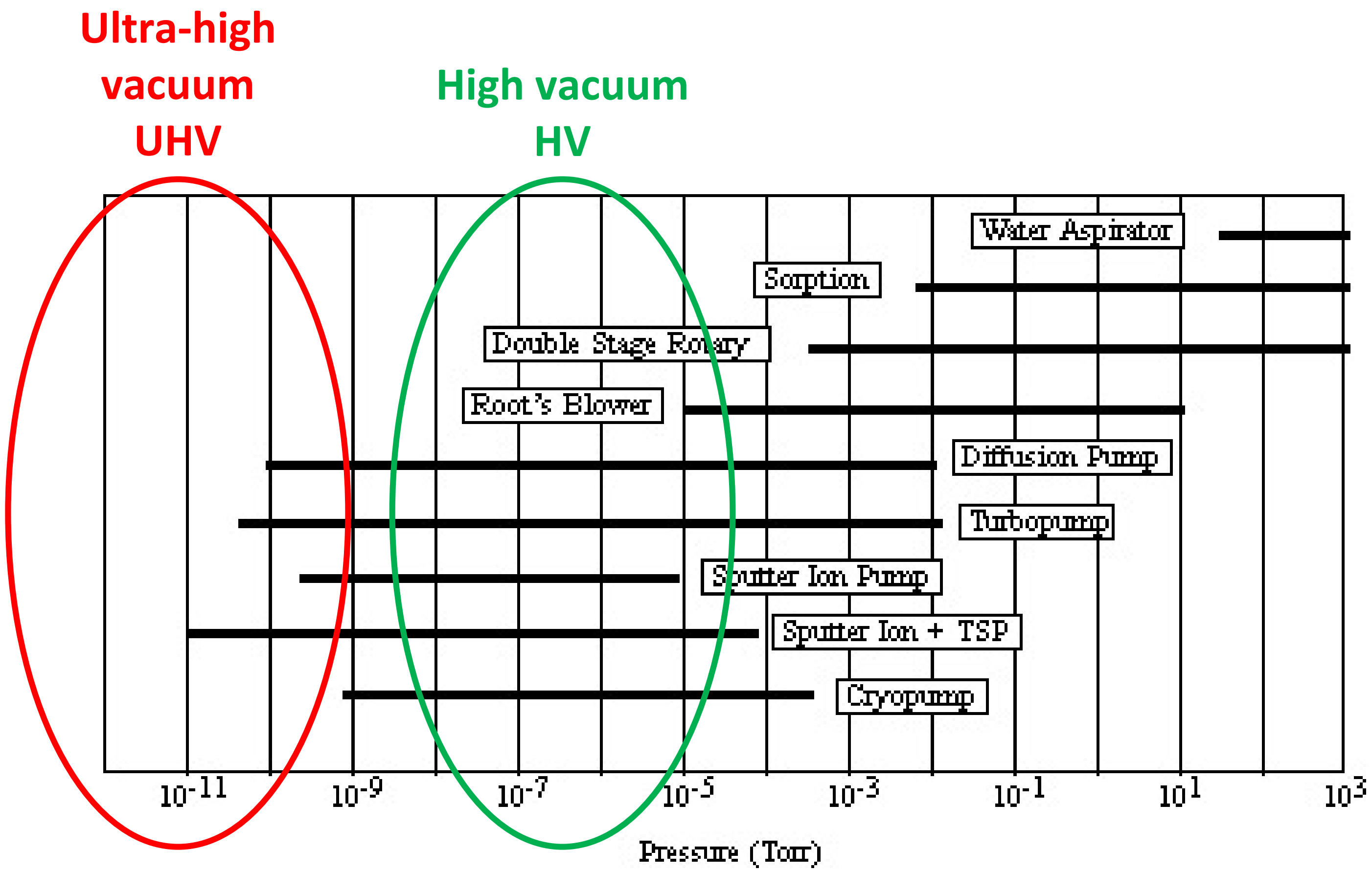
Leakage current

At low pressures, such current can be comparable or much higher than the pressure-dependent ion current. It can arise from both external sources, such as power supply, the connecting cable or the high-voltage feedthrough, and internal sources. Among internal sources, the metallization of ceramic insulators during operation. The main cause is the emission of free electrons from the titanium surface when strong electric field is applied.

C. Paolini et al., *Ion getter pumps*, Proceeding of the 2017 CERN-Accelerator-School course on Vacuum for Particle Accelerators, Glumslov (Sweden)

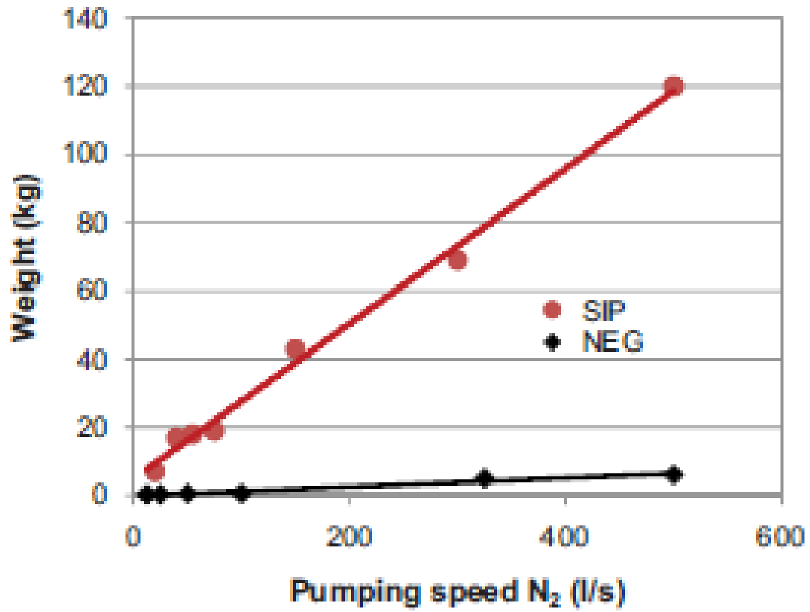
NEG – SIP COMBINATION: the NEXTorr® concept

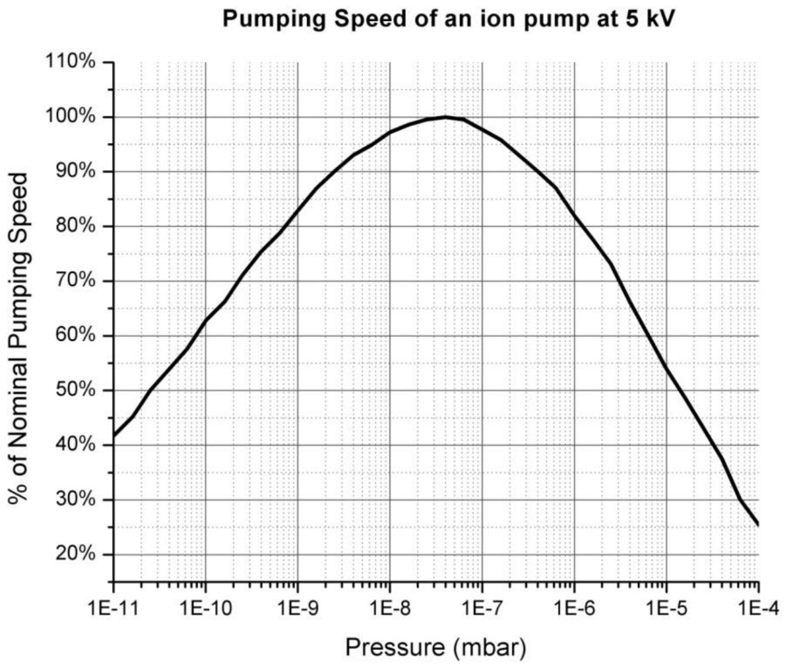
PUMPING SYSTEMS VS PRESSURE RANGE



How to get the most effective combination of pumps, in order to achieve UHV-XHV conditions?

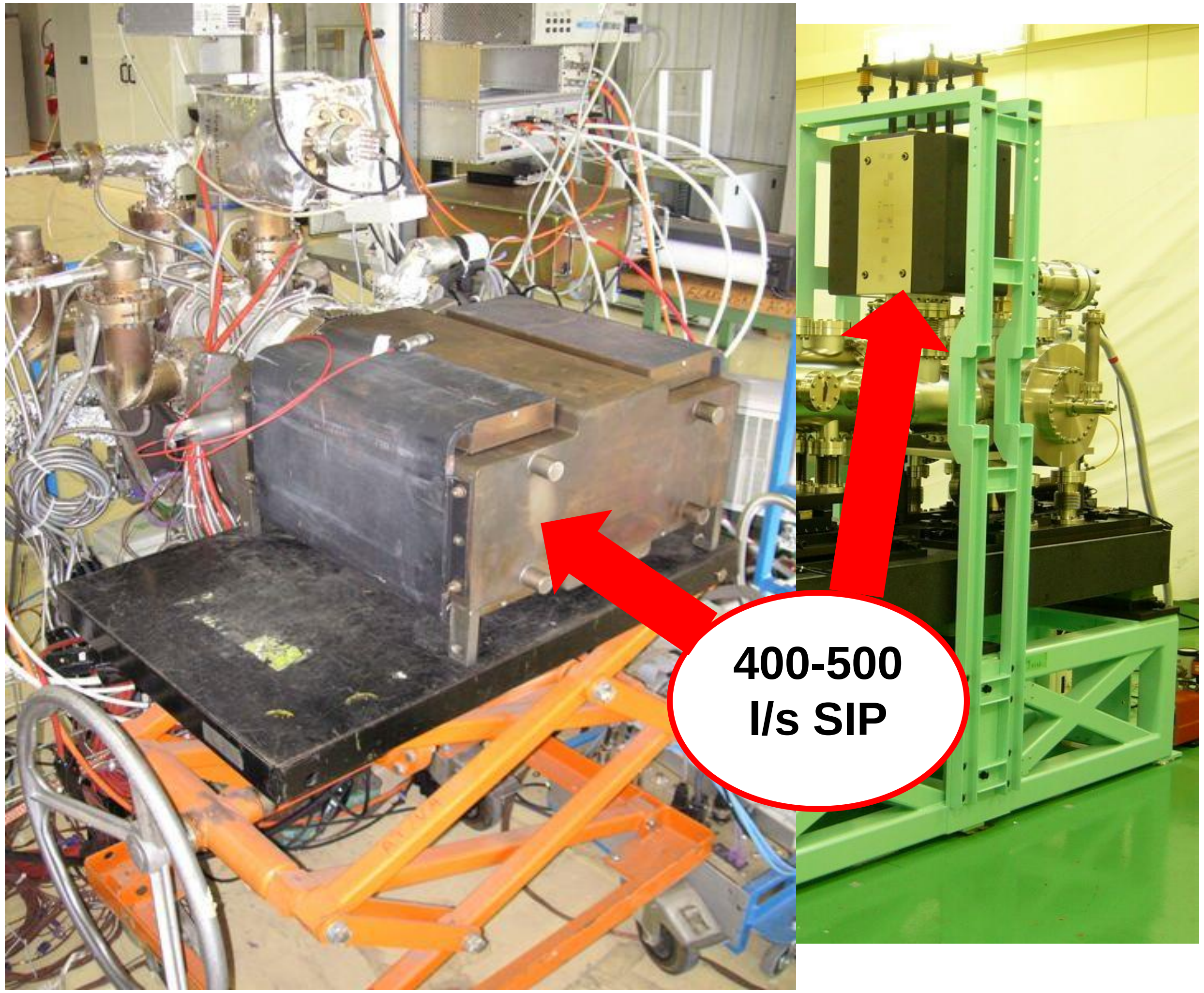
SPUTTER ION PUMPS VS NEG PUMPS





- In principle, a lower pressure can be obtained ensuring a higher pumping speed.
- SIPs and turbomolecular pumps (TMPs) can thus become **very large and heavy**.
- In UHV-XHV, moreover, the sputtering and compression processes of SIPs and TMPs, respectively, are less effective, resulting in a lower pumping speed compared to chemical pumps with the same dimensions.

SIPs may need space and weight support



Possible issues :

- Infrastructure for mounting
- Lifting
- Maintainence
- Powering
- Safety

SPUTTER ION PUMPS VS NEG PUMPS

Ion pumps have some limitations:

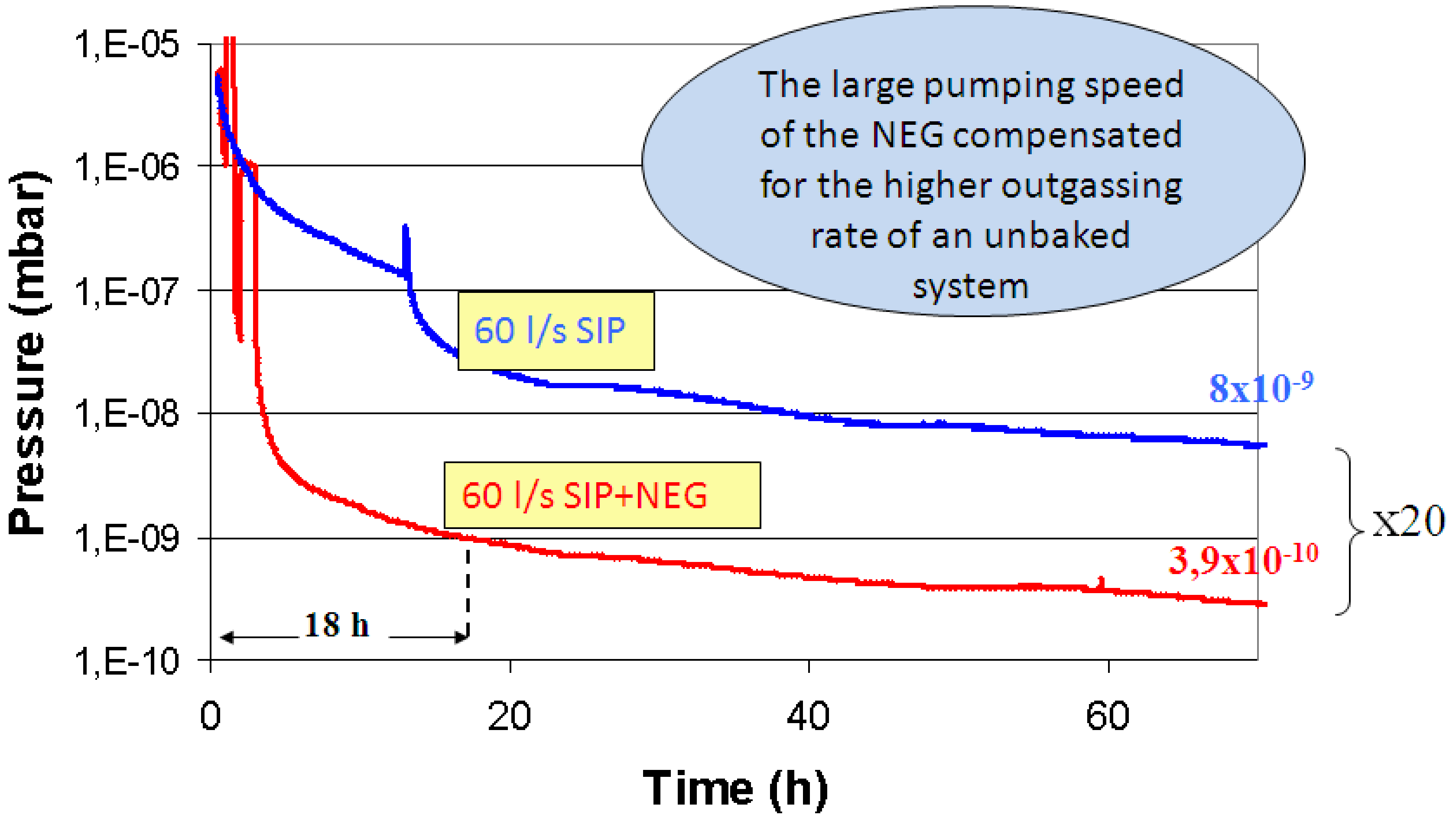
- large weight and size
- Ti particle emission
- instability effects
- decrease in the pumping efficiency below 10^{-8} mbar
- low pumping efficiency for H_2 (main residual gas in UHV-XHV systems)

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

On the other hand…

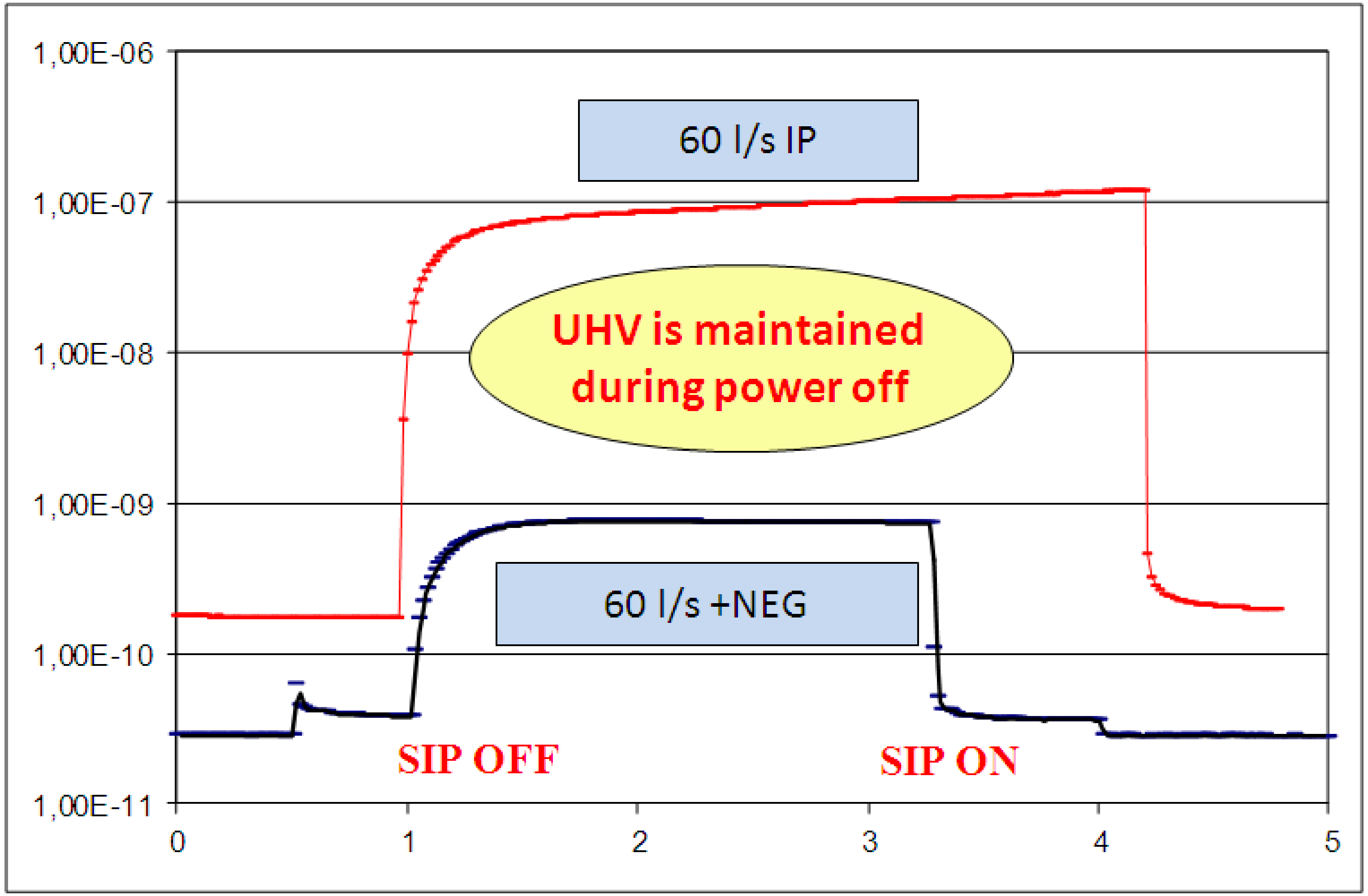
- NEG pumps do not sorb noble gases and methane, thus they are generally used in combination with other UHV pumps.
- **SIP technology is the most suitable to be *integrated* with NEGs**
  - It's a capture pump
  - Very popular technique to achieve UHV in vacuum systems

SIP+NEG: shorter pump-down



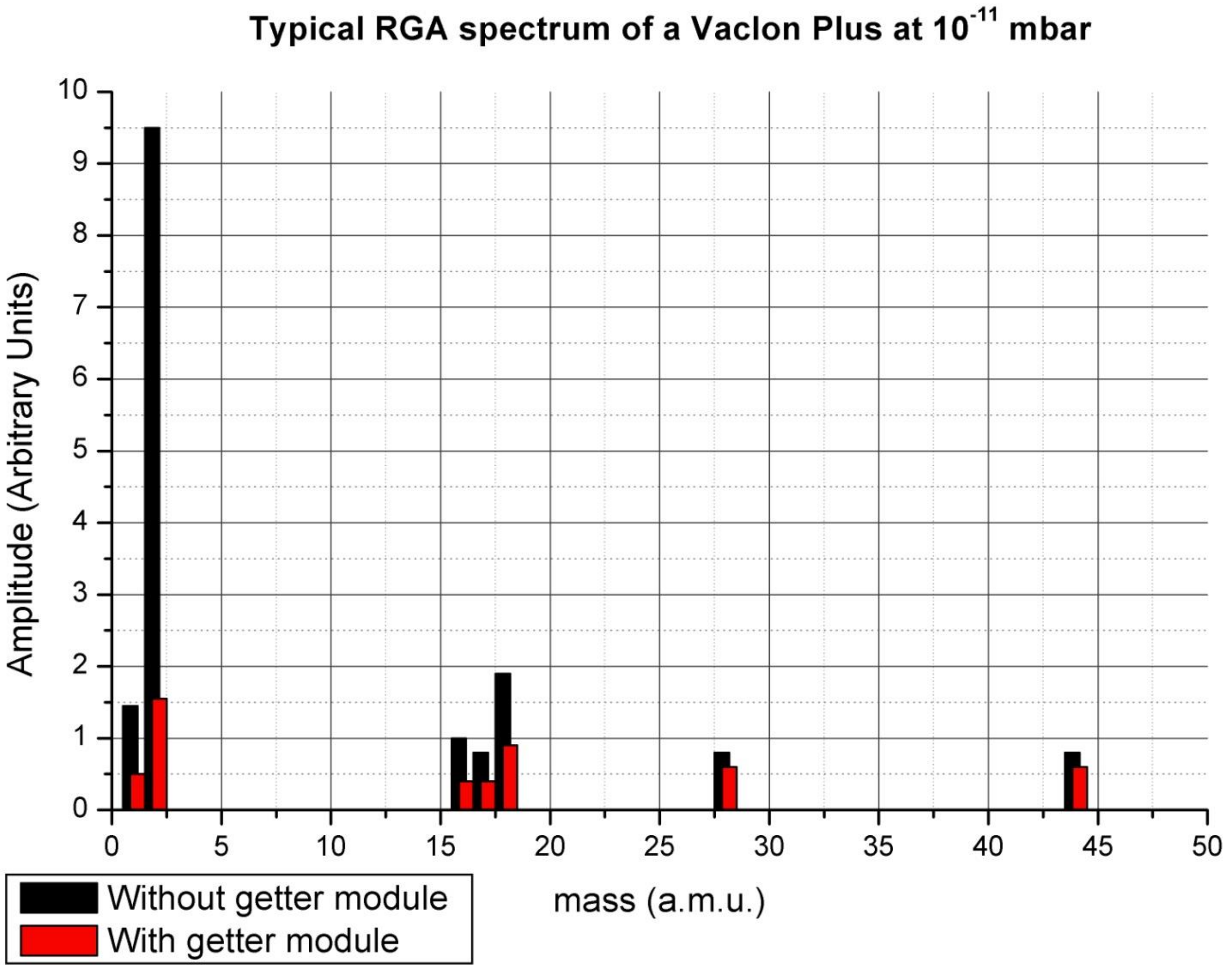
C.D. Park, S.M. Chung, P. Manini, J. Vac. Sci. Technol. A, 29 (1), 11012 (2011).

SIP+NEG: pressure rate of rise (SIP off)



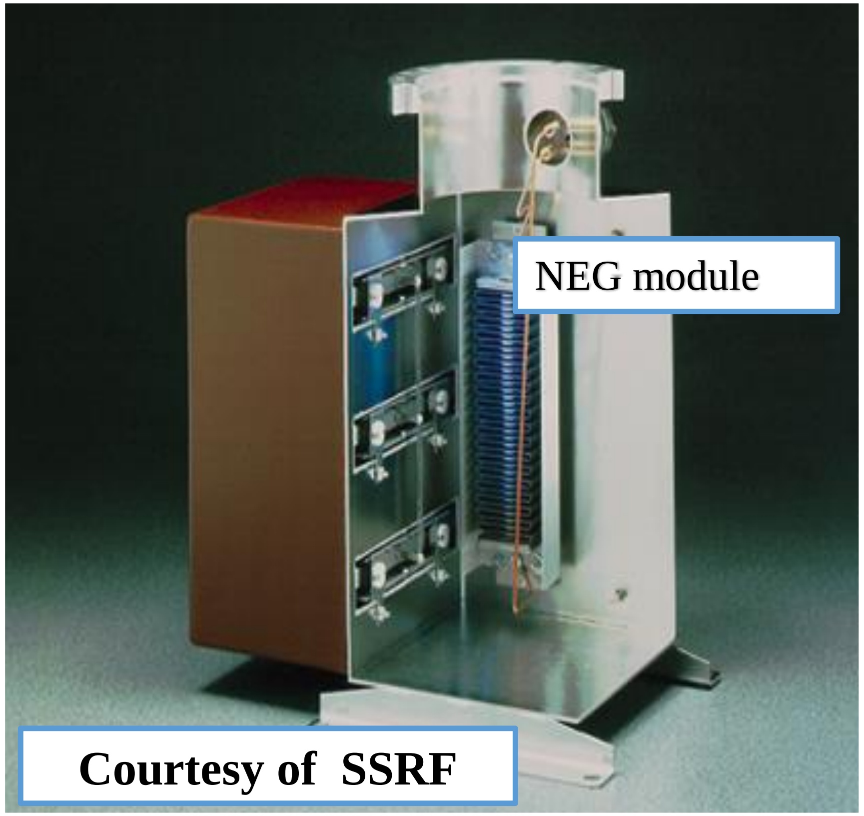
C.D. Park, S.M. Chung, P. Manini, J. Vac. Sci. Technol. A, 29 (1), 11012 (2011).

SIP+NEG: residual gas



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

MINIATURIZATION: a key requirement in vacuum



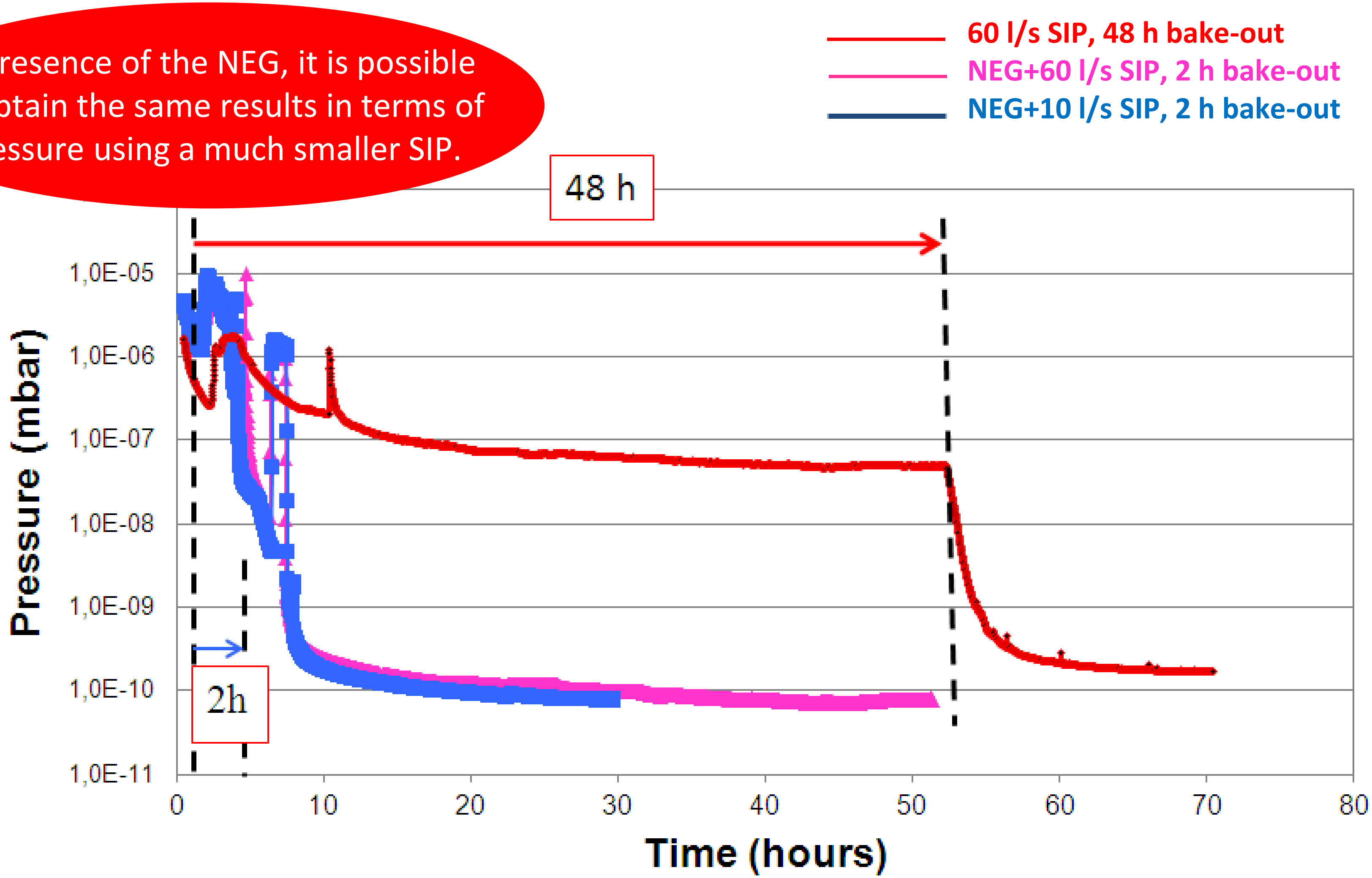
- NEGs are commonly mounted inside mid-size or large SIPs through dedicated ports
- However this approach:
  - Does not solve space / weight issues
  - The NEG effective speed is reduced

- Equipment are more and more **complex and "packed"**. The demand to reduce the size and weight of vacuum systems is increasing for industrial and scientific applications: even in very large research vacuum systems, like accelerators and 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

Compactness and performance -> conflicting issues

SIP+NEG: reducing SIP size

In presence of the NEG, it is possible to obtain the same results in terms of pressure using a much smaller SIP.



C.D. Park, S.M. Chung, P. Manini, J. Vac. Sci. Technol. A, 29 (1), 11012 (2011).

SIP+NEG: reducing SIP size

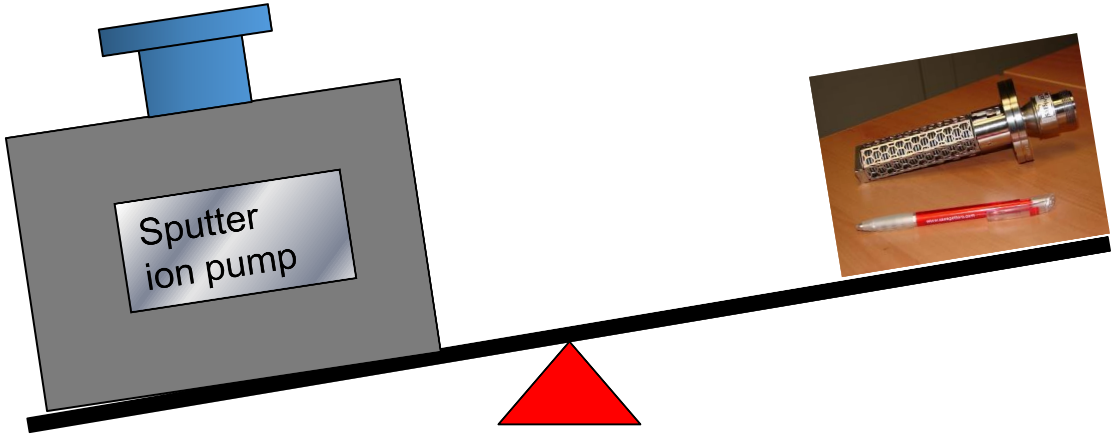
- In this study, no pressure difference was measured when reducing the SIP pumping speed from 60 l/s to 10 l/s, the NEG being the main factor to achieve ultimate vacuum.
- This is in agreement with Benvenuti and Chiggiato, who show that $<10^{-13}$ mbar can be achieved using NEGs as the main pump and leaving to small SIPs the ancillary task of removing CH_4 and argon, which cannot be pumped by the getter [1].
- The same authors also estimated that an ion pump with about 10 l/s for CH_4/Ar is sufficient to achieve 10^{-13} mbar in a 1 m^2 leak tight and well conditioned vacuum system [2].

A vacuum system can be kept in UHV-XHV conditions by NEG pumps assisted by small SIPs only

NEXTorr® concept

[1] C. Benvenuti, P. Chiggiato, J. Vac. Sci. Technol. A 14(6), 3278 (1996).
[2] C. Benvenuti, P. Chiggiato, Vacuum 44 (5-7), 507 (1993).

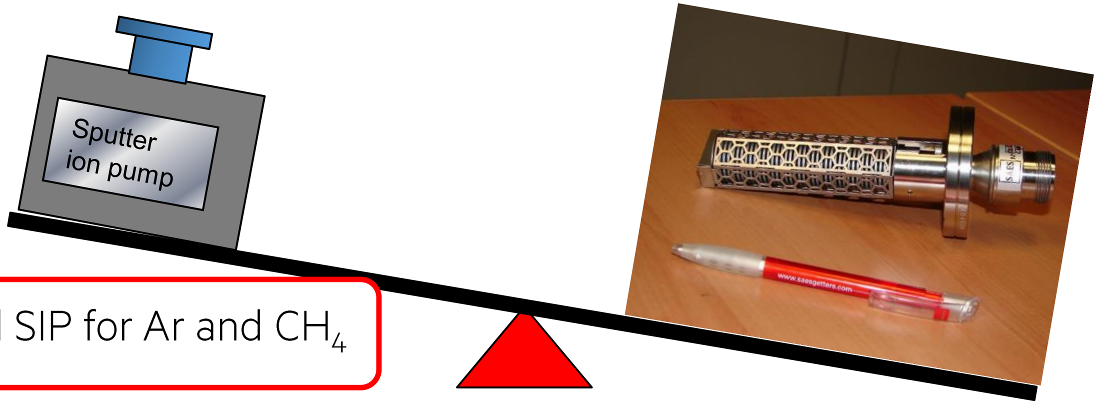
New approach in UHV systems



Traditional approach

Large pumping speed provided by the NEG as main pump (still compact)

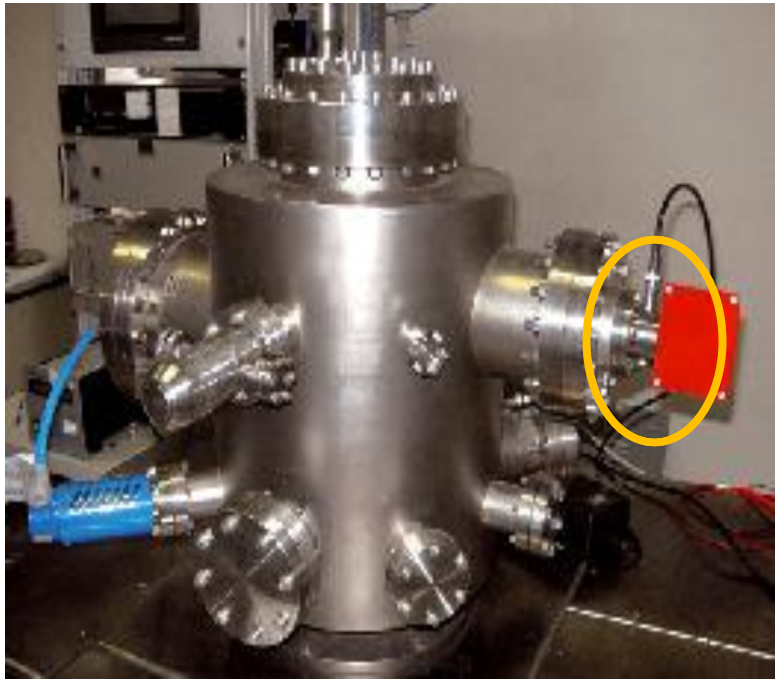
Innovative approach



Small SIP for Ar and CH_4

NEXTorr® pumps

SIP 120 l/s (H_2)



NEXTorr® 100 l/s (H_2)

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high vacuum

Bonucci et al, 57th AVS Conference, 2010.
Manini et al, Vacuum 94 (2013) 26-29.

The NEXTorr® family

- NEXTorr® is a patented (US 8,287,247 B) generation of pumps which combines, in a single, very compact and light package, a NEG element and a very small SIP.
- NEXTorr® pumps are available with St172™ (D series) and **ZAO® UHV** (Z series) disks, providing higher pumping speed and even lower particle release.
- Models featuring **ZAO® HV** for high vacuum are available too (HV series).
- Each NEXTorr® pump has a dedicated power supply and cables to activate the NEG and control the ion pump.

The NEXTorr® design **provides remarkable pumping synergies:**

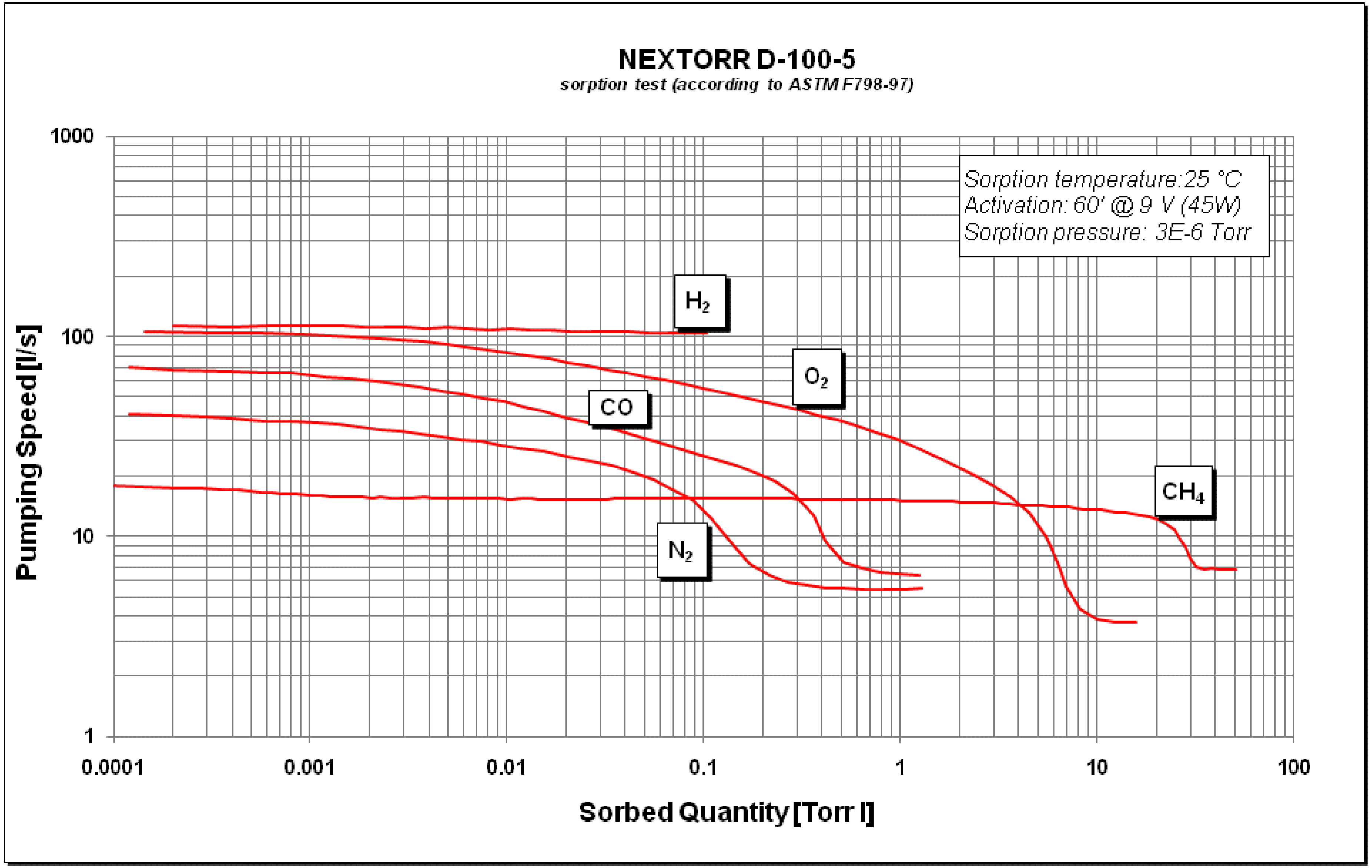
- The ion part pumps gases that the getter does not, so that the NEXTorr® pumps all gases
- Getter capacity is increased
- The getter element intercepts most of the emitted Ti particles
- Gases released by the ion pump during the operation are intercepted and removed by the getter element
- Increased pumping efficiency for H_2 , CH_4 and Argon
- Methane is dissociated in the plasma and a significant amount of H_2 released into the vacuum system is intercepted by the NEG.

How it looks like: NEXTorr® D 100-5 pump

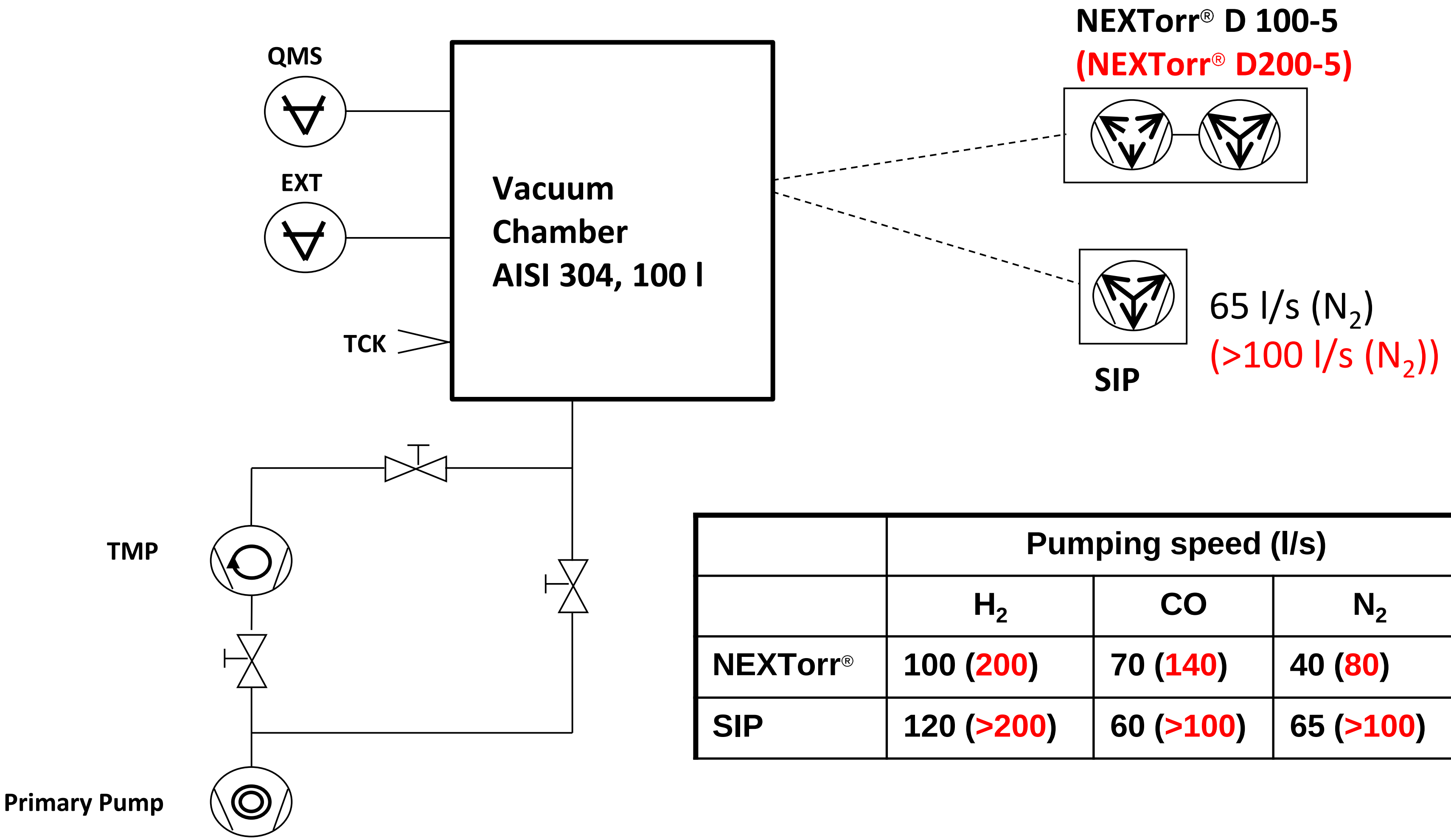
Total weight (magnets included)	**2,2 kg**
Volume	**0,5 l**

	Initial pumping speed (l/s)	
Gas	NEG activated	NEG saturated
H_2	**100**	**6**
CO	**70**	**6**
N_2	**40**	**5**
CH_4	**15**	**7**
Argon	**6 (0,3)**	**6 (0,3)**

How it looks like: NEXTorr® D 100-5 pump - typical sorption curves



NEXTorr® vs SIP: experimental setup



	Pumping speed (l/s)		
	H_2	CO	N_2
NEXTorr®	100 (200)	70 (140)	40 (80)
SIP	120 (>200)	60 (>100)	65 (>100)

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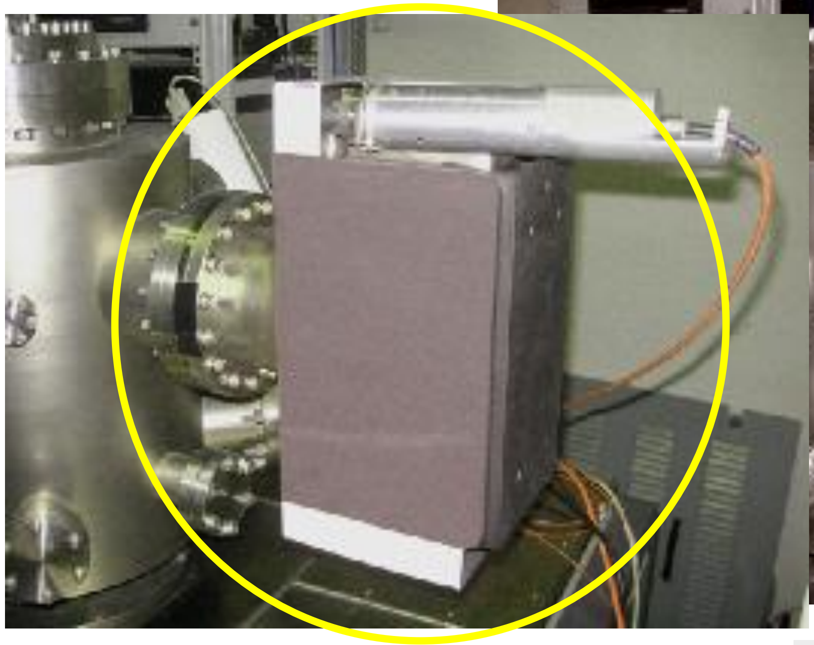
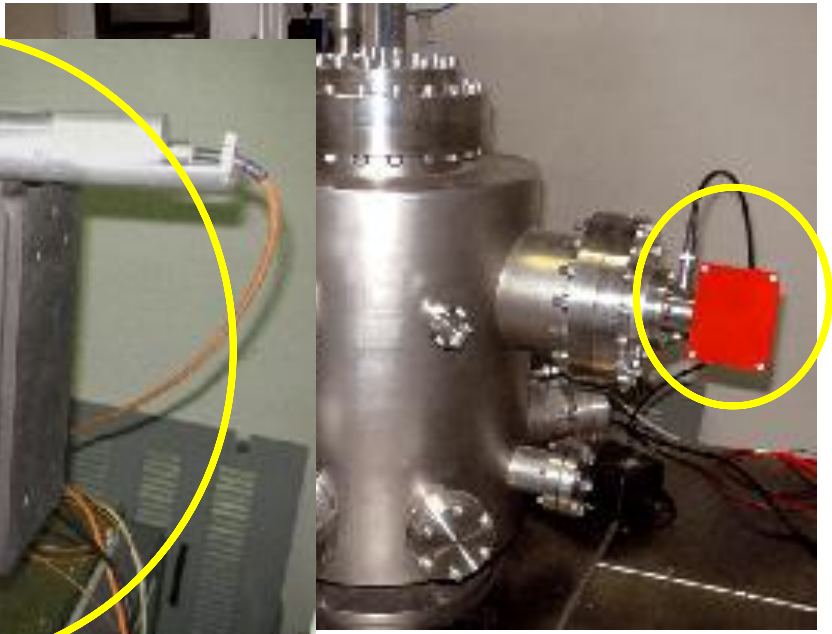
NEXTorr® D100-5 vs SIP: experimental setup and procedures

- Bench baked at 170 °C for 24 h under pumping. NEG element of the NEXTorr® pump kept hot (300°C) during the bake out.
- After bake, pressure recorded for several days.
- Rate of rise test (RoR) carried out to measure the pressure build up in both systems in absence of power.
- Two blank runs carried out to measure pressure evolution without the SIP or the NEG.
- Total and partial pressures recorded with a QMS.

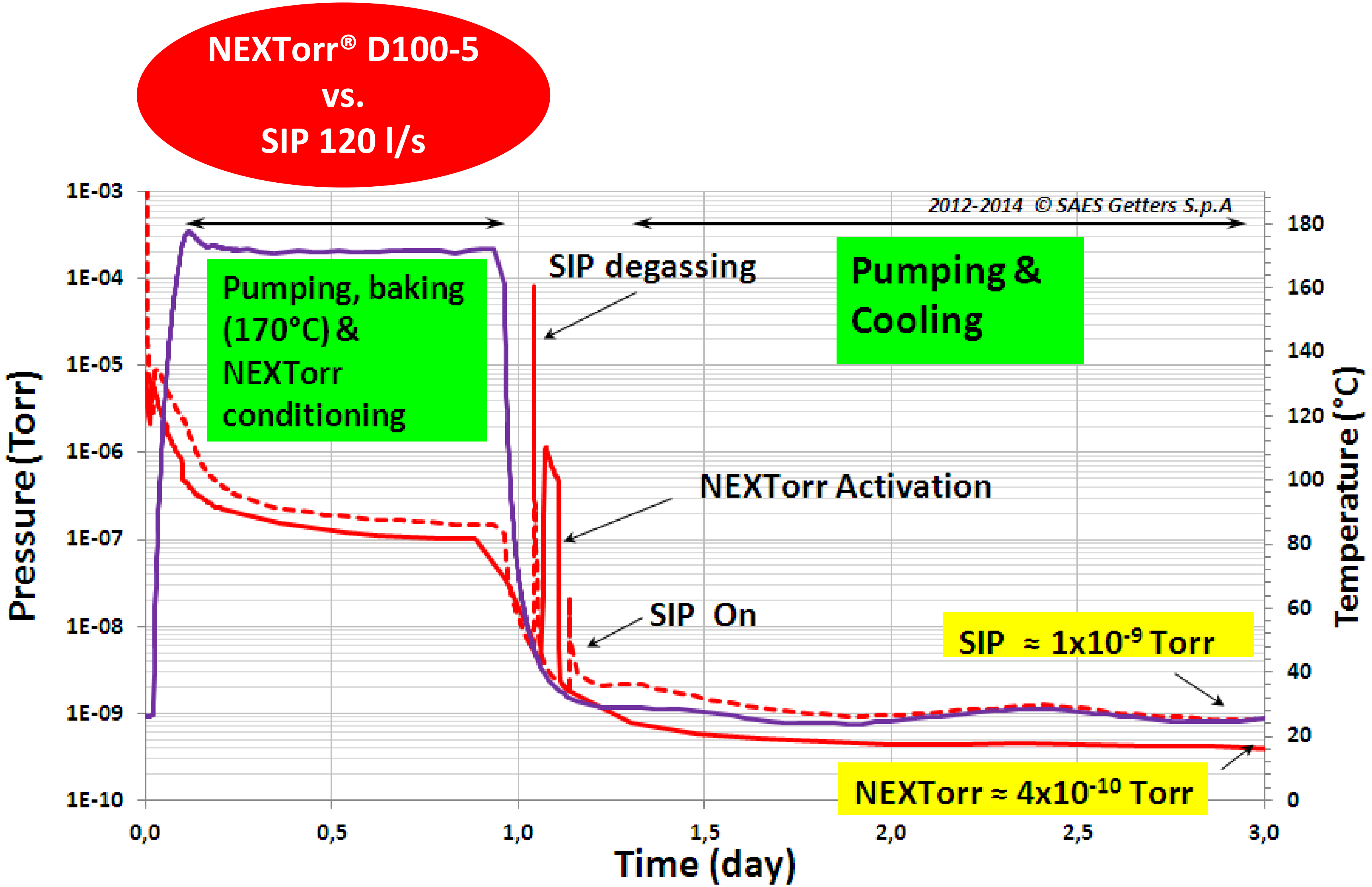


SIP - 120 L/s (H_2)

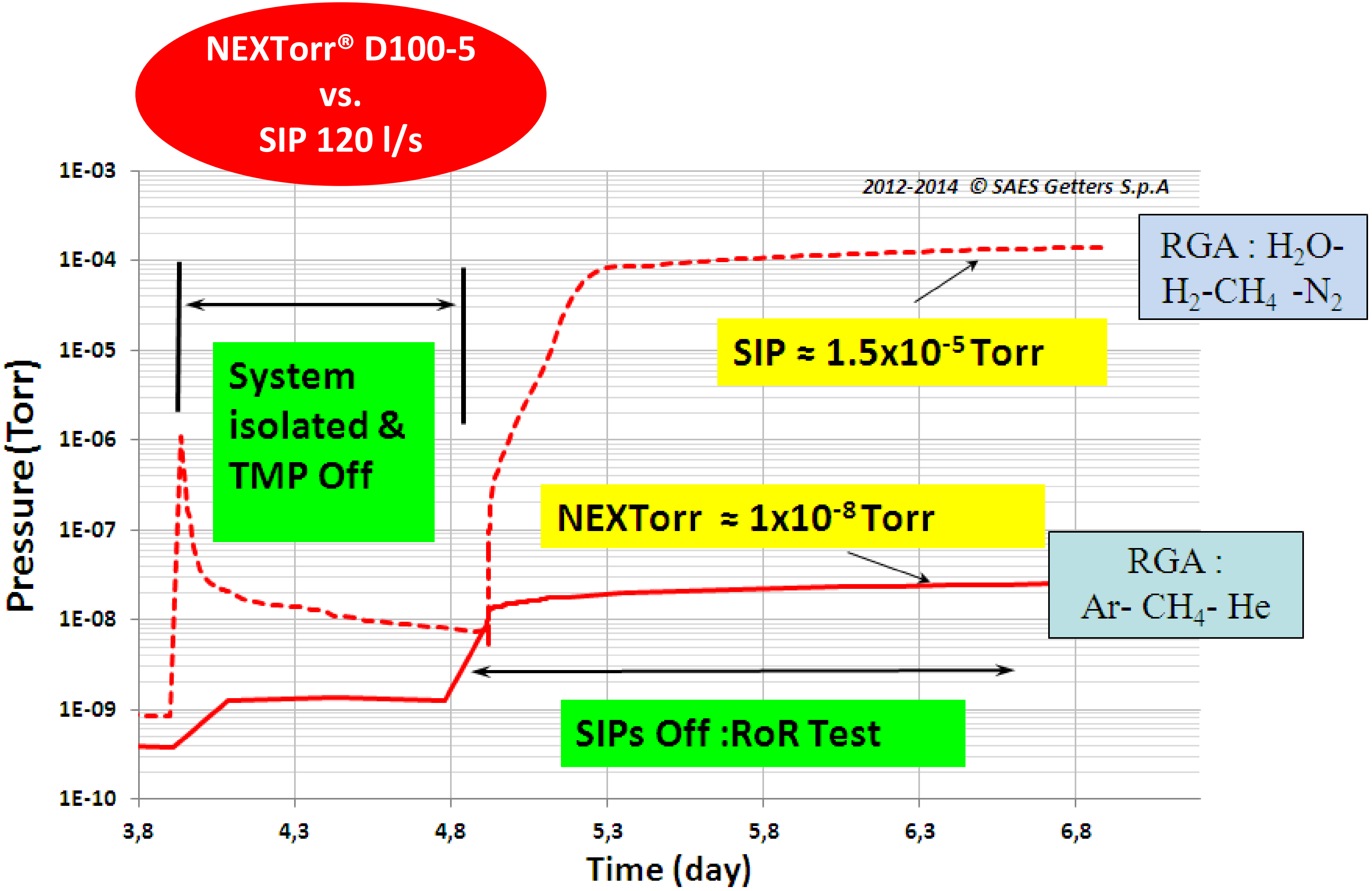


NEXTorr® – 100 L/s (H_2)

NEXTorr® vs SIP: pump-down time

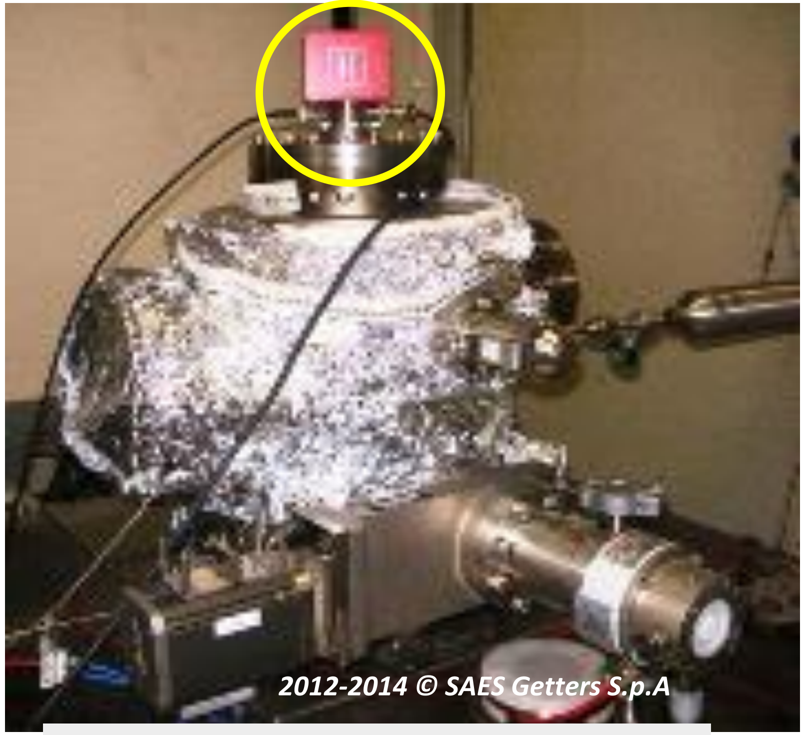


NEXTorr® vs SIP: pressure rate of rise (SiPs off)



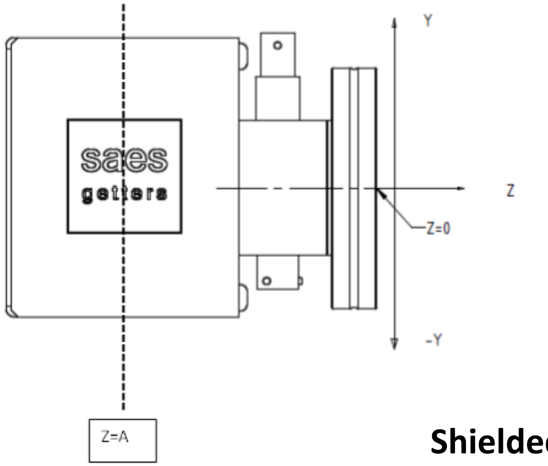
NEXTorr® D200-5 vs SIP: experimental setup

SIP - 200 l/s (H_2)

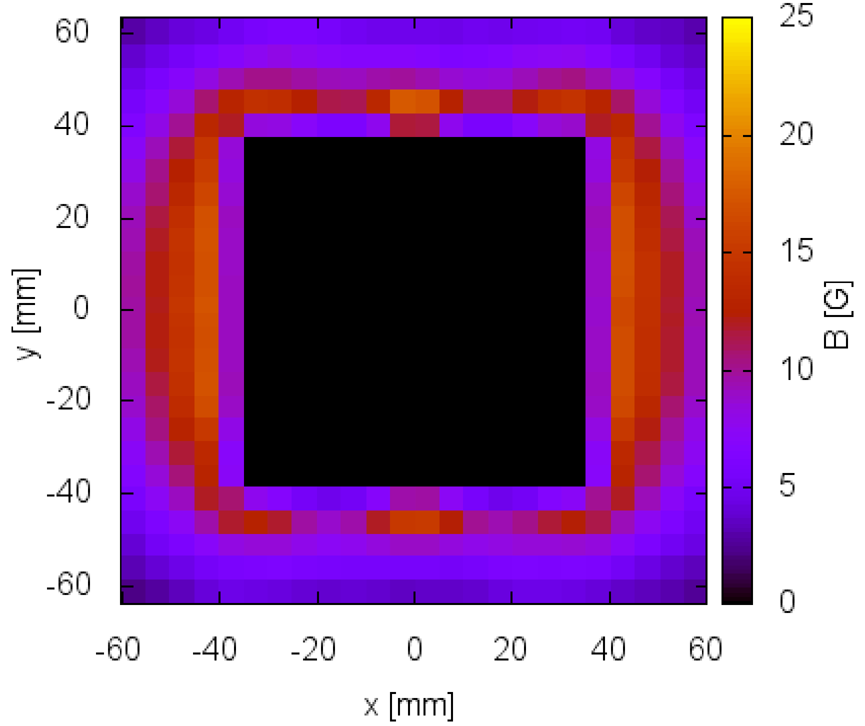


NEXTorr® D200-5 - 200 l/s (H_2)

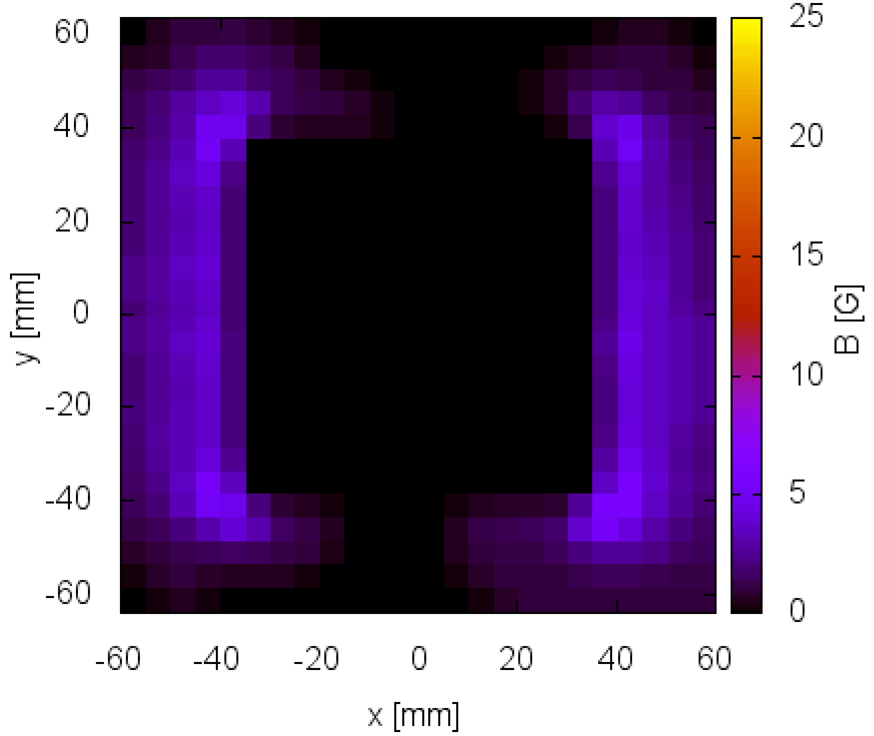
Stray magnetic field in NEXTorr® SIPs



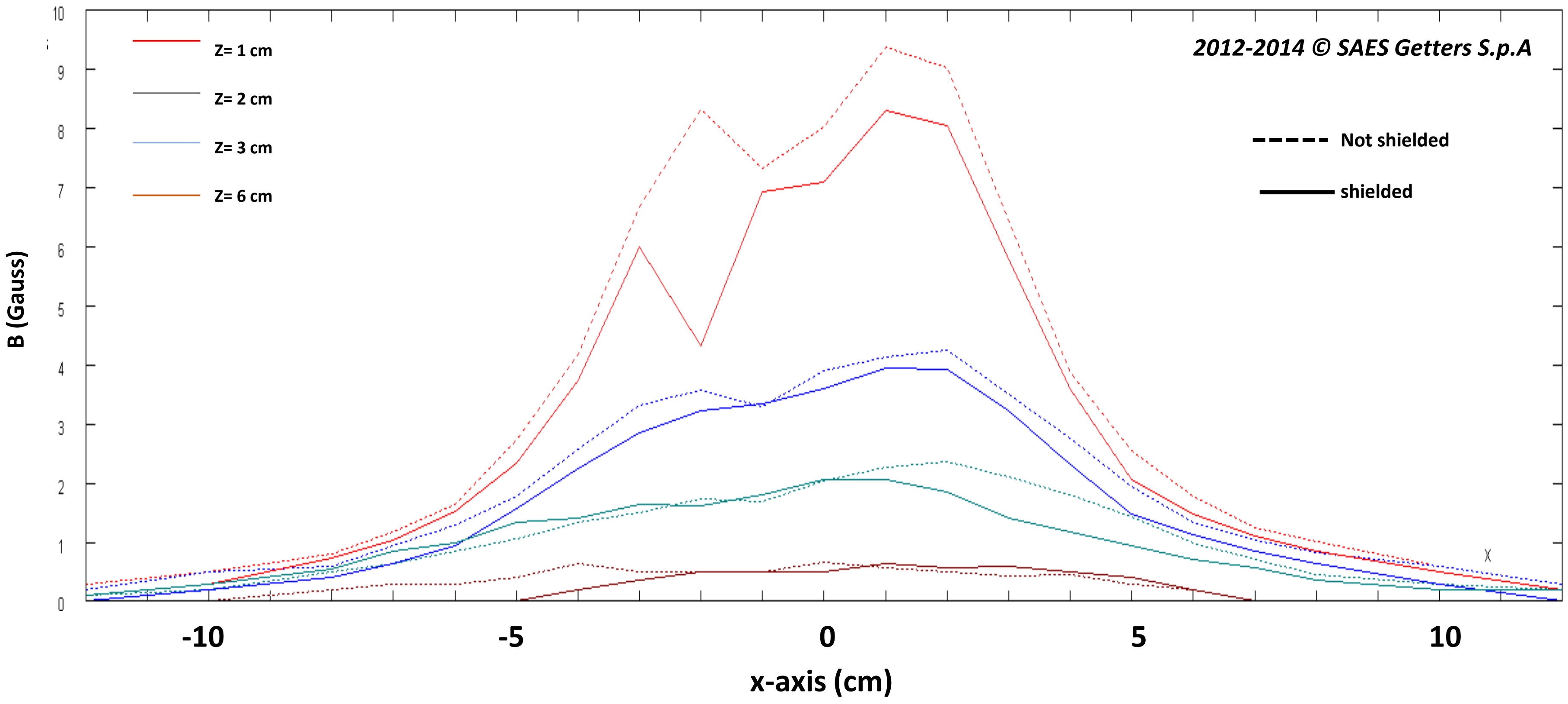
Not shielded



Shielded



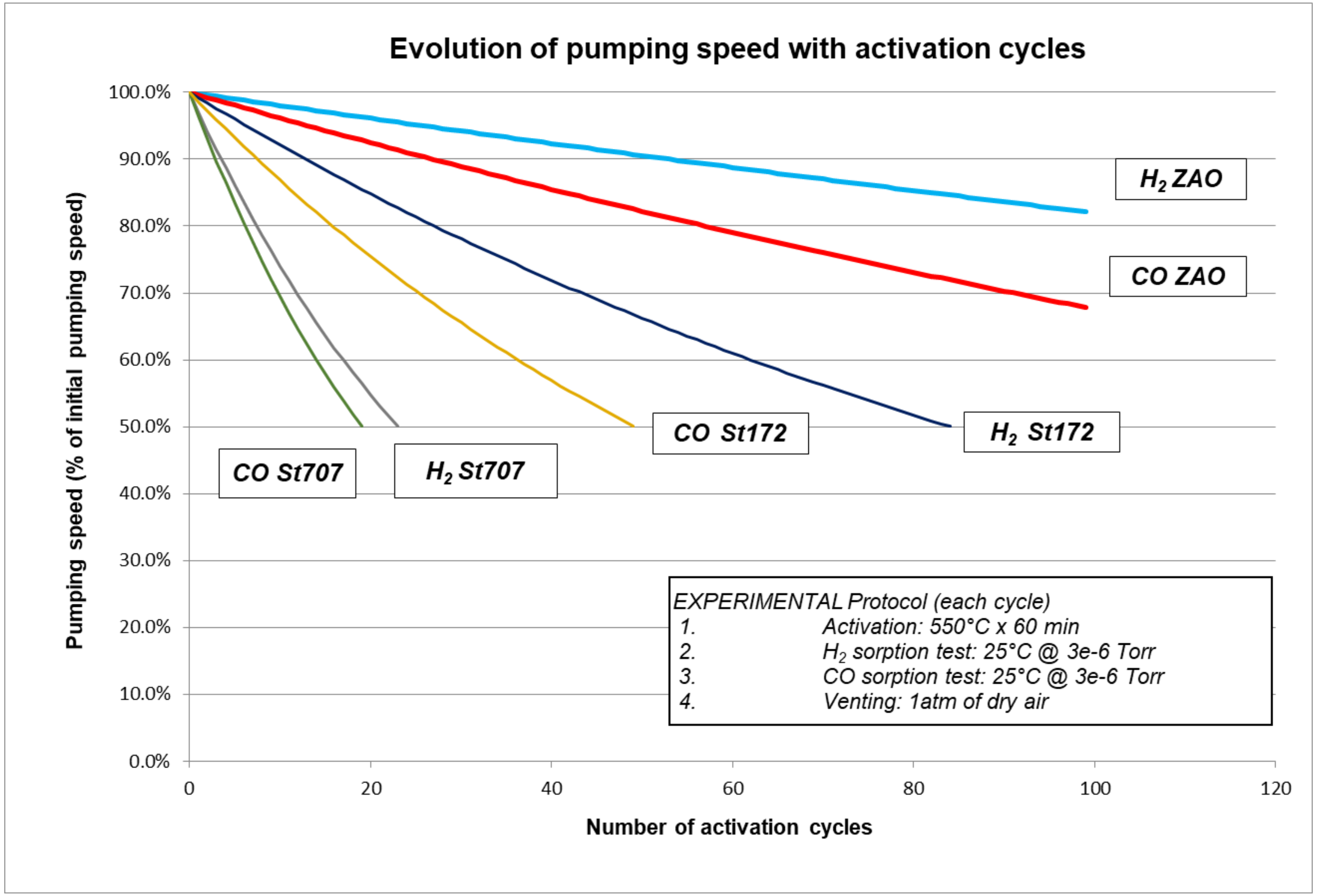
Stray magnetic field in NEXTorr® SIPs



APPLICATION OF NEG PUMPS:

1. **Reactivation and outgassing**
2. **Procedures**
3. **Particle release**
4. **Pump-down with no auxiliary pumps**
5. **Applications**

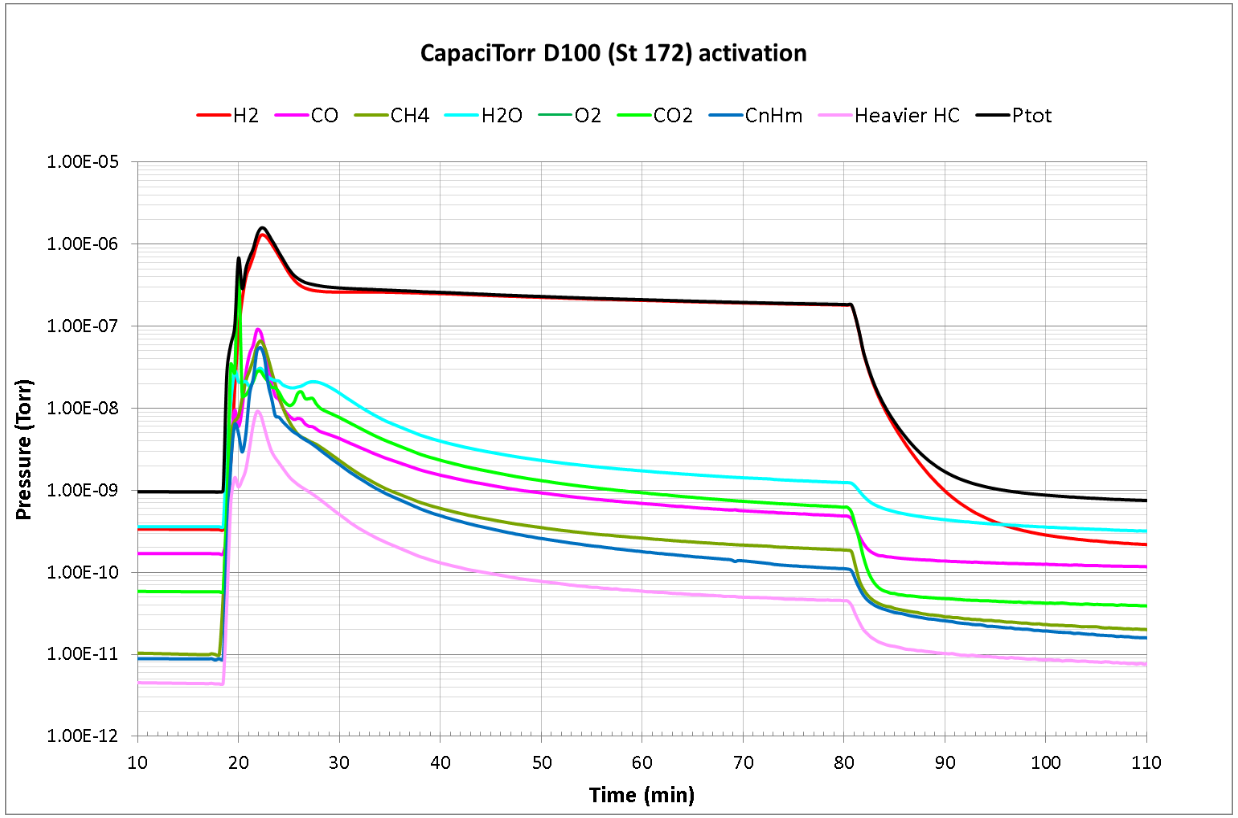
RESISTANCE TO REACTIVATION CYCLES



- ZAO® is much robust to reactivation cycles with venting (>100 cycles with less than 40% of pumping speed reduction on CO).
- In any case, the progressive pumping-speed reduction can be compensated by slightly increasing the activation temperature (e.g., 450→550 °C).

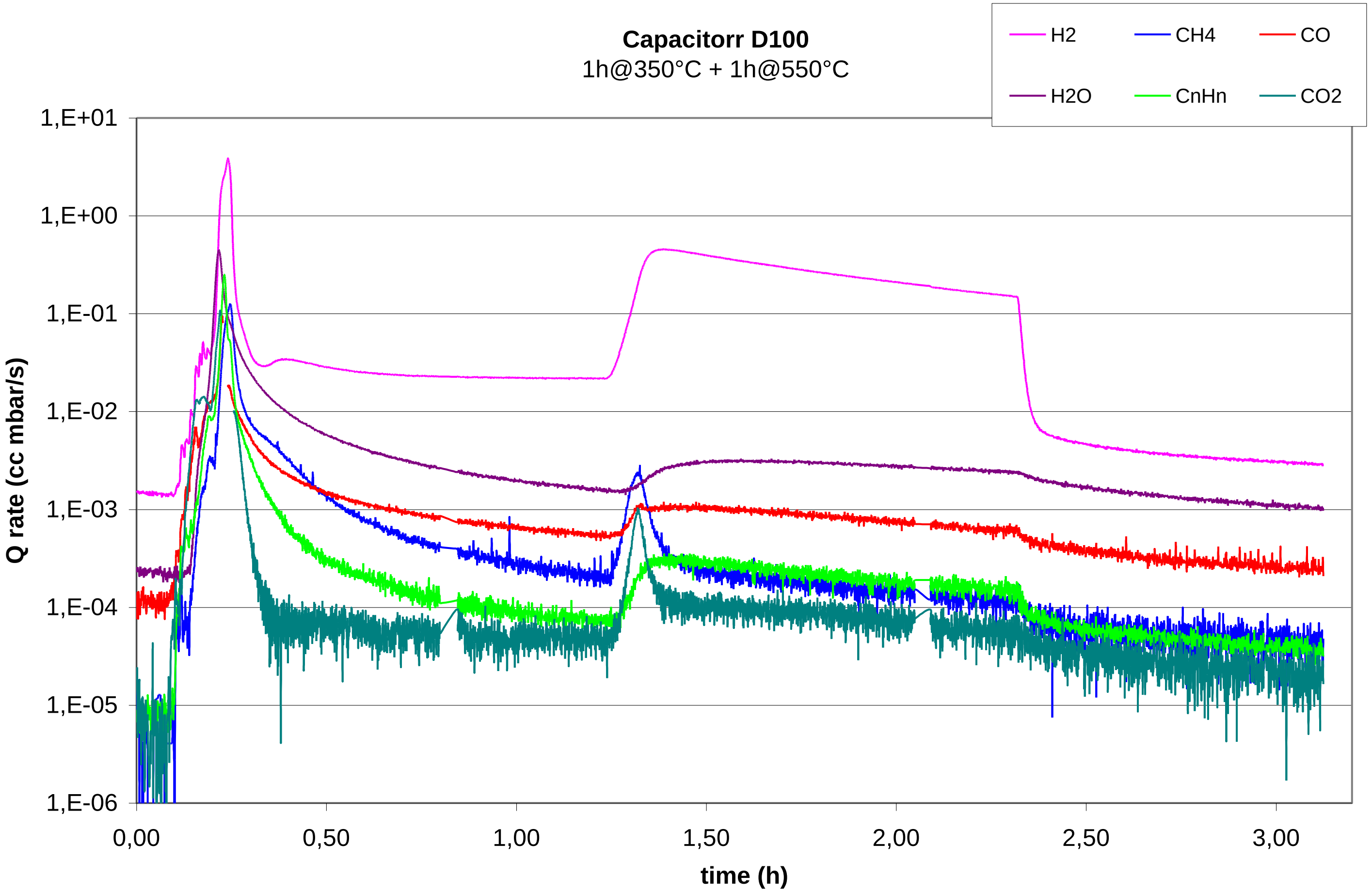
NEG OUTGASSING PROPERTIES: residual gases during activation

- *First desorption peak at 250°C - 300°C and approaching full activation temperature*
  Most of the physisorbed 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 PROPERTIES: 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 of the power supply. If this is not possible, a standard bake out is acceptable.



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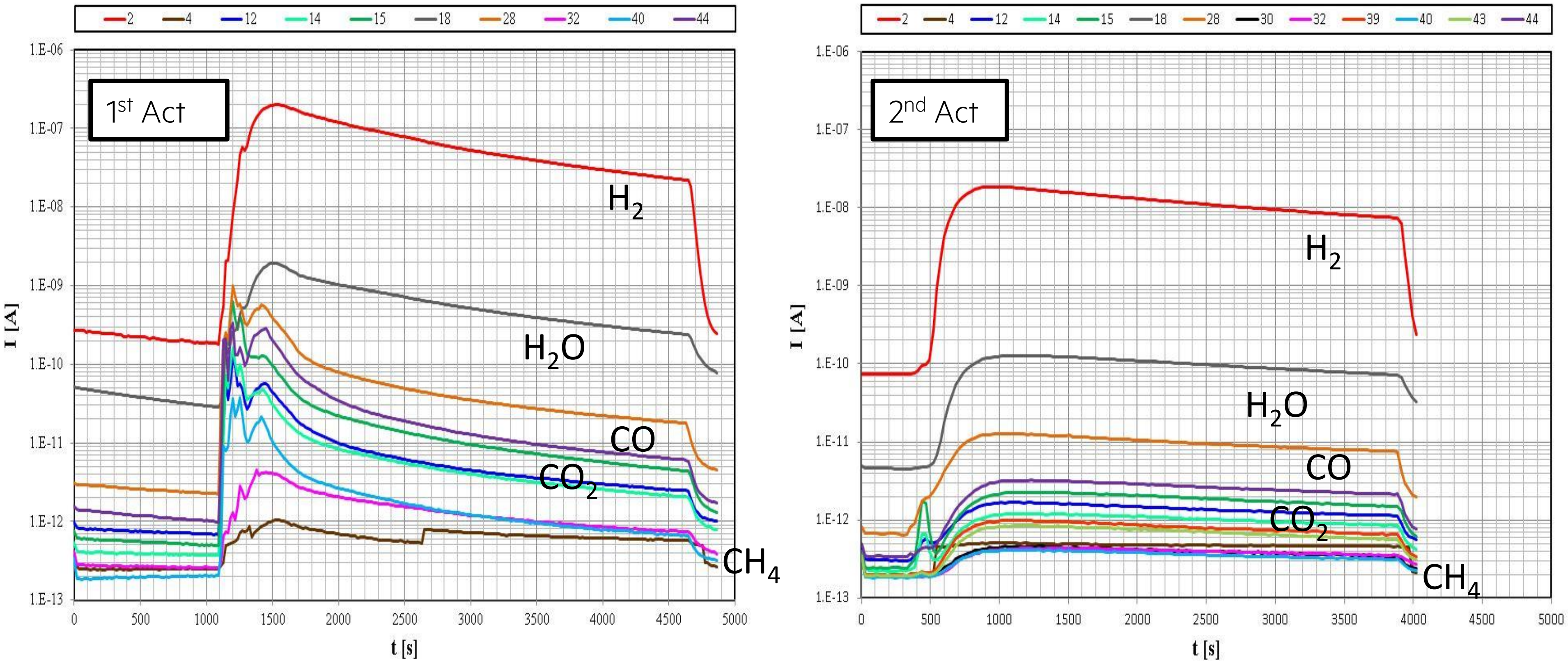
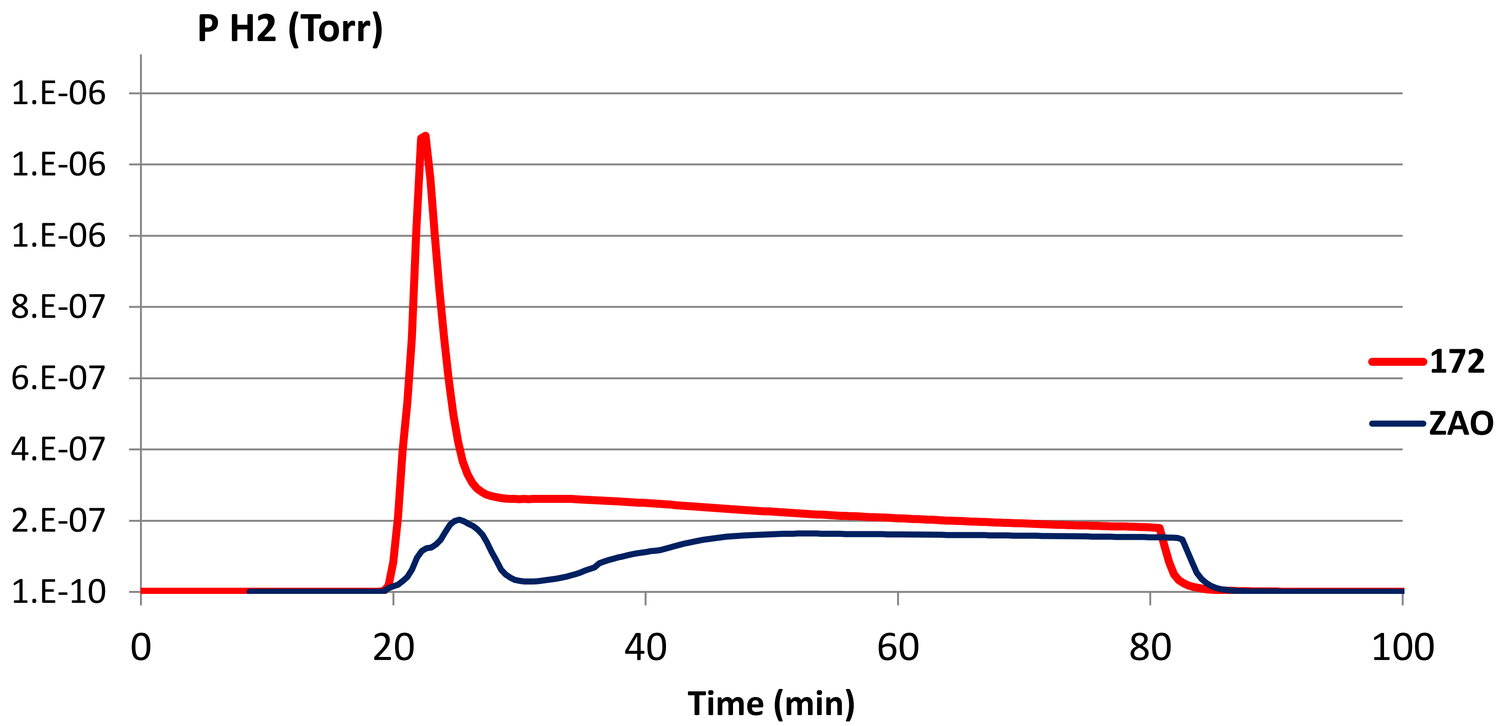
NEG OUTGASSING PROPERTIES: Gas desorption after the first activation



Gas emission is about a factor 10-20 smaller after the first activation.
Slightly lower ultimate pressure is expected.

NEG OUTGASSING PROPERTIES: ZAO® vs St172™ alloy

- H_2 evolution during activation is about 5 times smaller for ZAO® compared to St172™.
- The total amount of released H_2 is also a factor 2 smaller.



ACTIVATION PROCEDURES: practical hints

During the NEG pump **activation:**

- **any ion pump should** be **off**
- **TSPs** (if present) should be **operated after** the NEG pump **activation:** if TSP are operated before, due to the partial release of hydrogen by NEG pump activation, TSP will sorb a large amount of hydrogen which will be released during normal operation

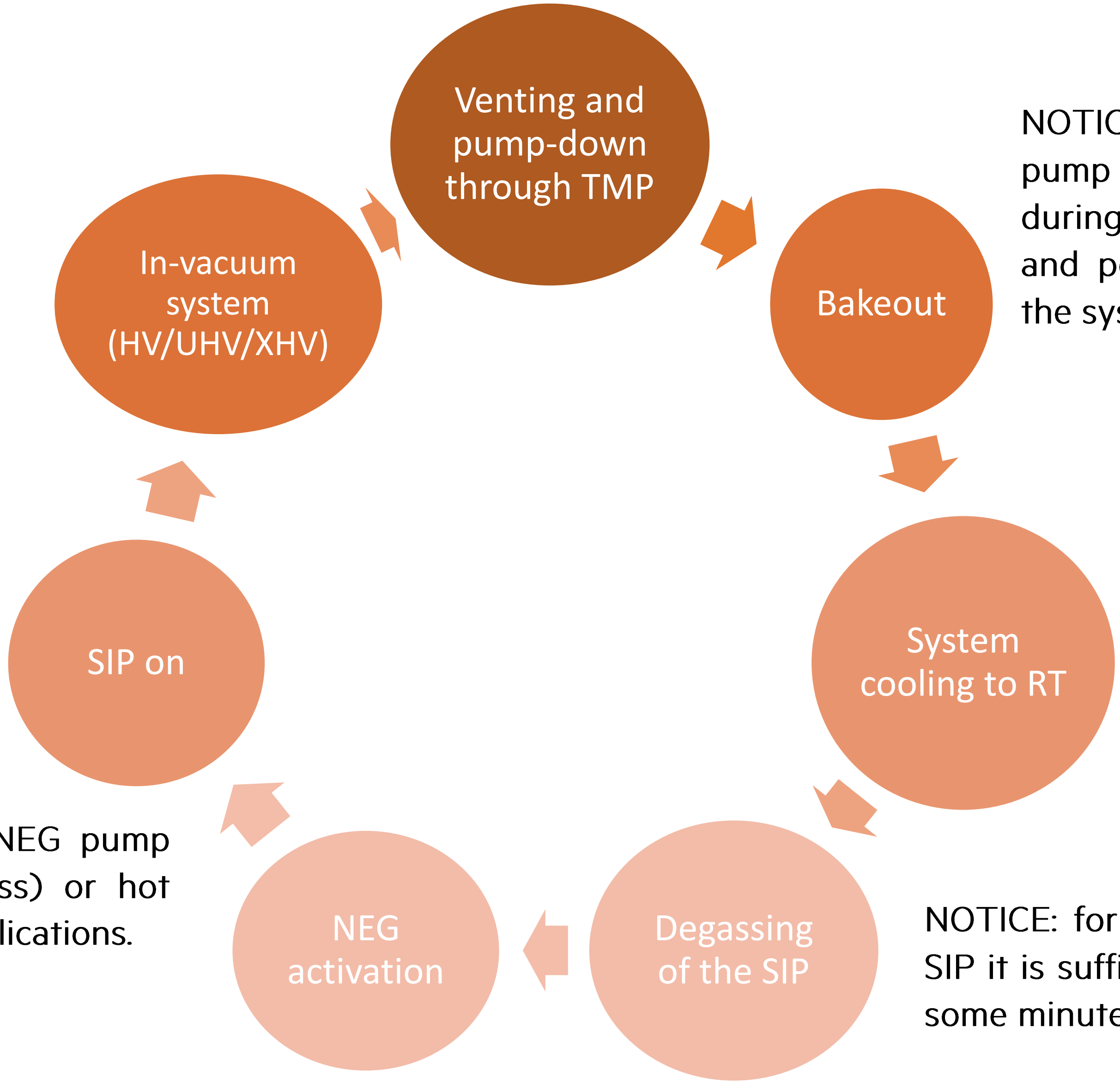
Two **activation processes** will be described

- Baked vacuum system after venting
- Unbaked vacuum system after venting

All described procedures are **considered best-practice**, but they can be adjusted depending on:

- System characteristics (surface/volume)
- Needs (time and pressure target)
- Expected outgassing species from the system…

Procedures: baked vacuum system after venting



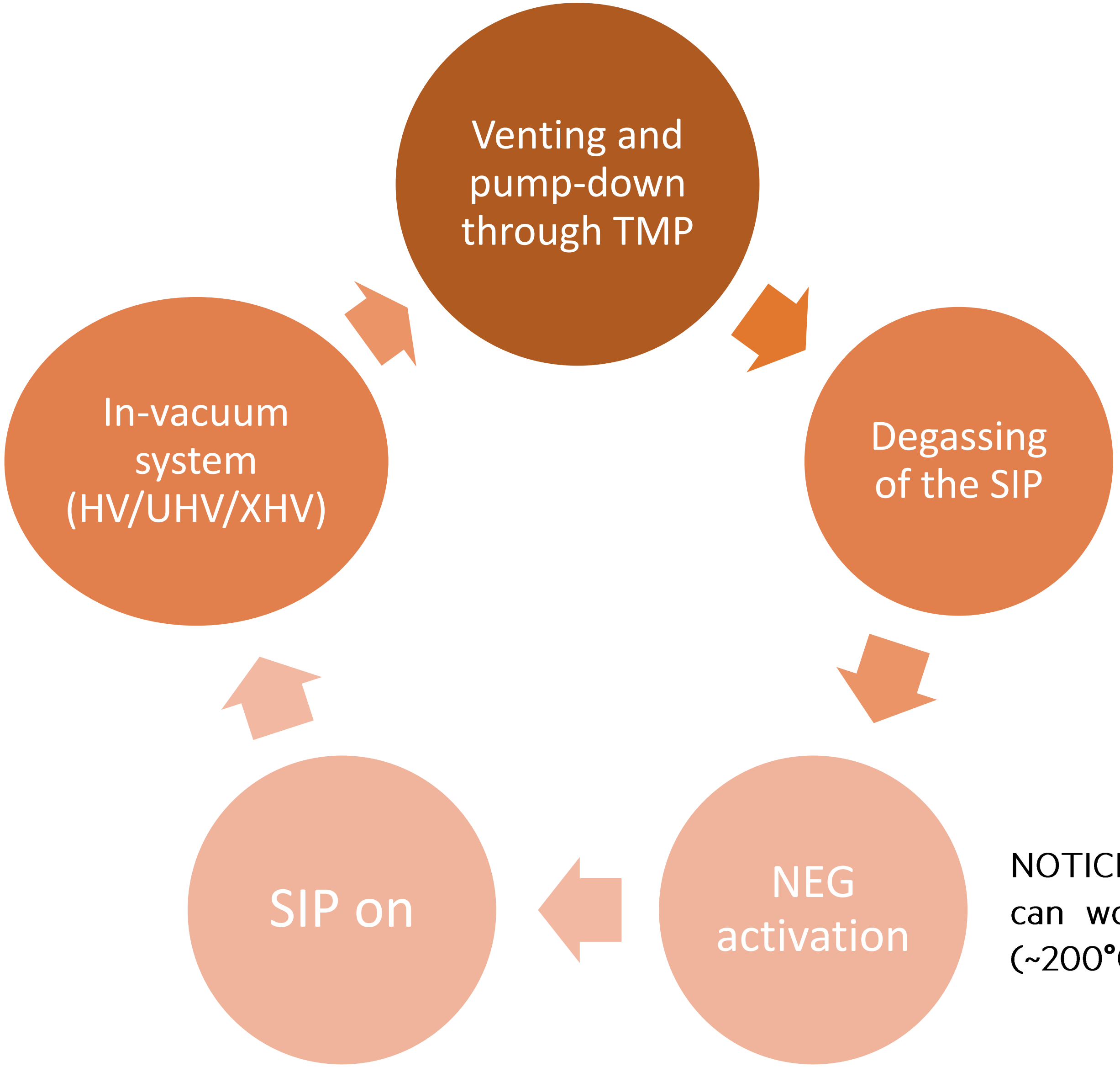
NOTICE: in principle, the NEG pump can be activated also during the bakeout process and possibly reactivated after the system has reached RT.

NOTICE: also SIPs should be baked (check compatibility with max. magnets temperature or remove them). If it's not possible, it's better to keep it on during the bakeout.

NOTICE: for the degassing of the SIP it is sufficient to keep it on for some minutes, then switch it off.

NOTICE: after activation, NEG pump can work at RT (powerless) or hot (~200°C) in case of HV applications.

Procedures: unbaked vacuum system after venting



NOTICE: for the degassing of the SIP it is sufficient to keep it on for some minutes, then switch it off.

NOTICE: after activation, NEG pump can work at RT (powerless) or hot (~200°C) in case of HV applications.

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NEG in particle-sensitive systems: why particles might be an issue?

Particles can create severe mechanical, electromagnetic and optical issues:

- They can generate electric shorts, sparks and act as field emitter tips under high electric fields.
- On silicon wafers they can change properties of the deposited layers, create opens, breaks, morphological defects.
- They can contaminate masks and optical systems, in EUVL or electron beam masking tools, reducing resolution and introducing optical artifact.
- Particles can create abrasion, loss of tightness in load lock systems.

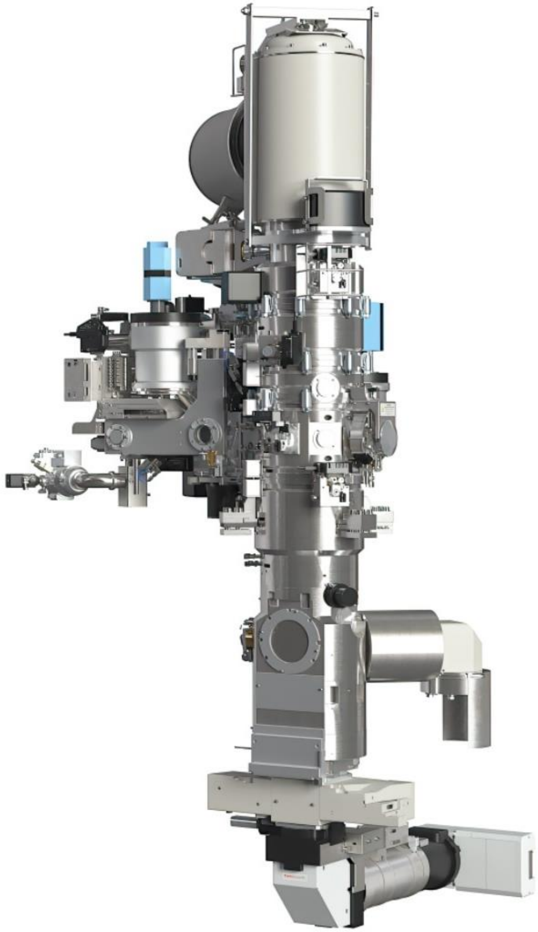
Particle-sensitive systems: some examples

A variety of industrial and scientific applications is particle-sensitive:

- X-ray inspection systems and tubes.
- Metrological and inspection tools (SEM, CD SEM, TEM).
- Photolithographic equipment (e-beam equipment...).
- Load lock and transportation vessel.
- Portable analytical systems (e.g. mass spectrometers).
- Large research facilities (particle accelerators, synchrotrons, fusion machines...).

Courtesy of Wilson Laboratory, Cornell

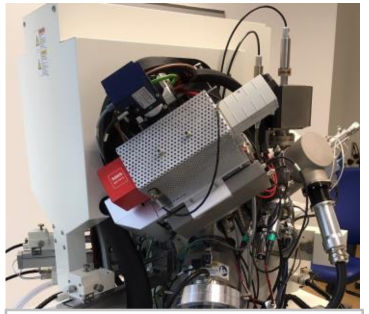
Courtesy of RAITH: EBPG Plus ebeam lithography system



Courtesy of THERMOFISHER: KRIOS G4 TEM

NEG pumps are widley used in particle-sensitive systems

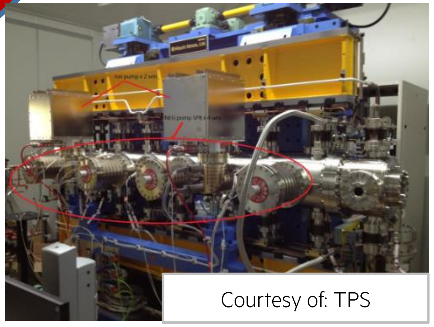
No maintenance nor vibrations



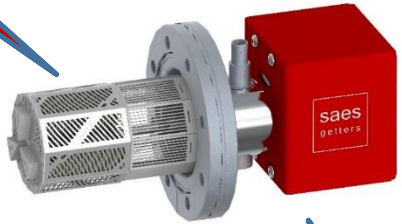
Courtesy of: TOFWERK AG and CARL ZEISS GmbH

High pumping speed and trapping efficiency for H2

Courtesy of: PREVAC

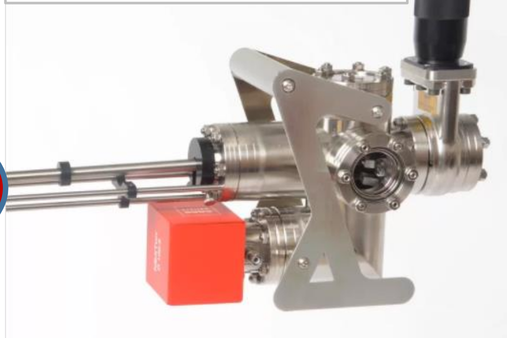


Courtesy of: TPS

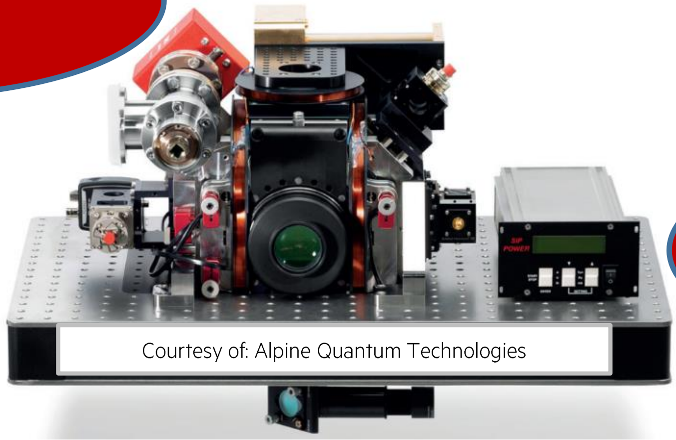


No power supply in working conditions

Extreme compactness



Courtesy of: SCIENTA OMICRON



Courtesy of: Alpine Quantum Technologies

Negligible magnetic interference

St172™: tests with particle counters in air/in vacuum (DESY)

A dedicated test to qualify Capacitorr® D 400 (St 172™) for SRF cavities and particle sensitive applications was carried out at DESY.
Tests were carried out :

- With a particle counter in air to assess compatibility of the pump to ISO classes
- With a particle counter under vacuum to measure particle emission during the real operation of the pump (e.g. conditioning and activations)

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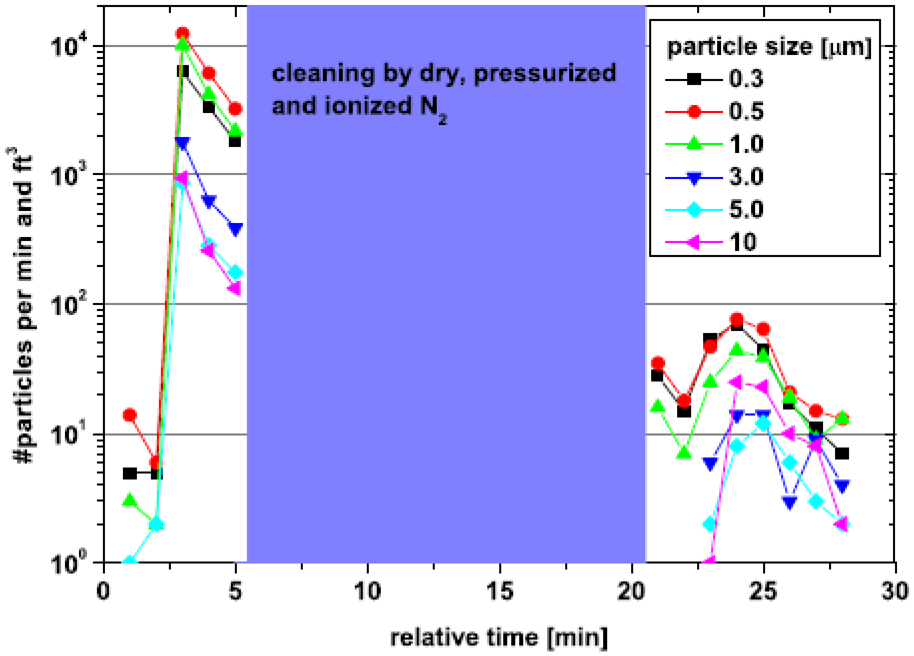
S. Lederer et al., *Particle generation of Capacitorr® pumps*, IPAC 2017

St172™ particle tests in air (DESY)

- The pump was cleaned by blowing dry ionized Nitrogen at 3 bar, inside a clean room of class ISO5.
- Particles were measured by the MetONE 2400-6 counter, able to detect particles ranges of 0.3, 0.5, 1.0, 3.0, 5.0 and 10.0 µm, operating with an air flow of 1 cfm.



Compatibility with particle-free systems and superconducting accelerator modules

- After about 15 min cleaning, the number of emitted particles is strongly reduced, and compatible with a ISO4 clean room.

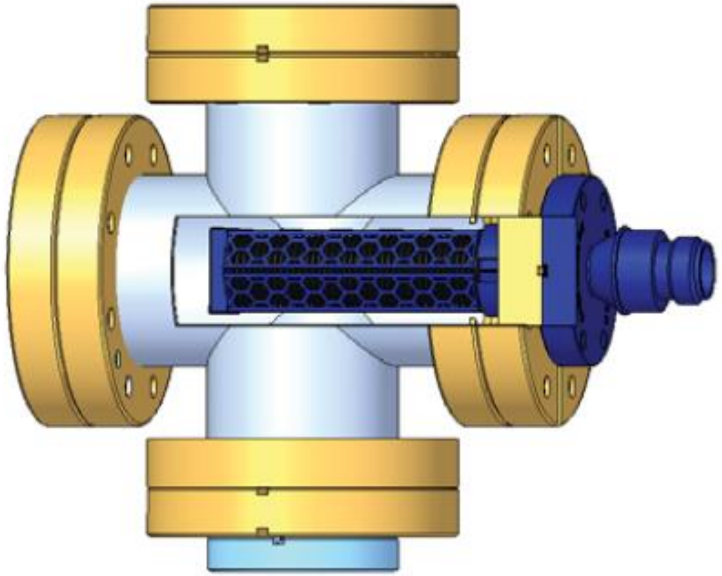
S. Lederer et al., *Particle generation of Capacitorr® pumps*, IPAC 2017

St172™ particle tests in vacuum (DESY)

- Particle creation during conditioning and activation of the D-400 pump was monitored by the in-vacuum counter XYT 70XE. The detectable particle size ranges are 0.17, 0.25, 0.3, 0.5 and 1 μm.

- Particle release was monitored in continuous during the 1 h conditioning at 200°C followed by 1 h activation at 450°C (pressure was below 10^{-5} mbar).

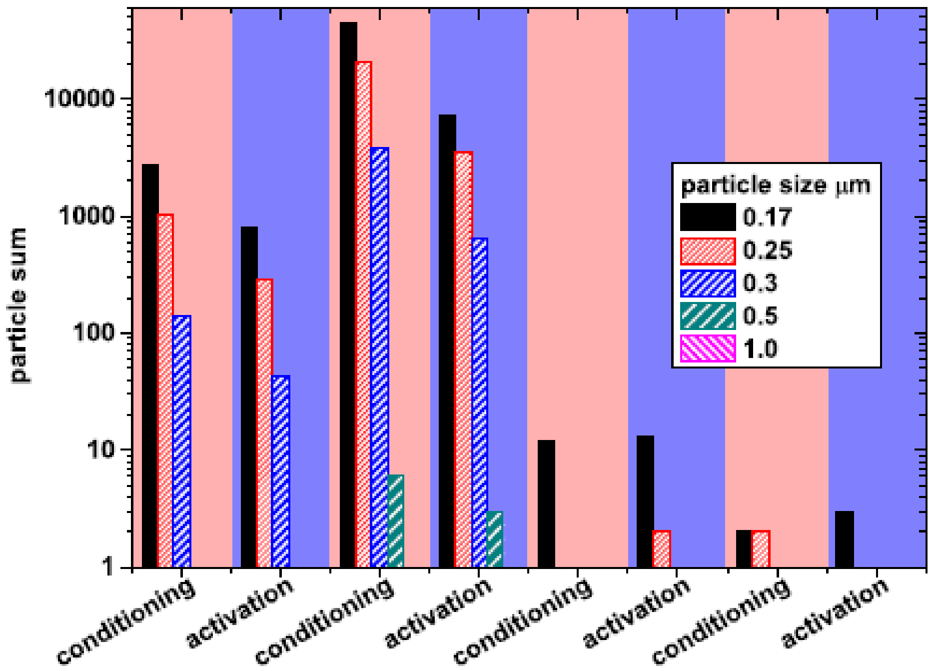
- The NEG pump was mounted horizontally into a DN63CF cross. The in-vacuum particle counter is connected to the bottom port of the cross.

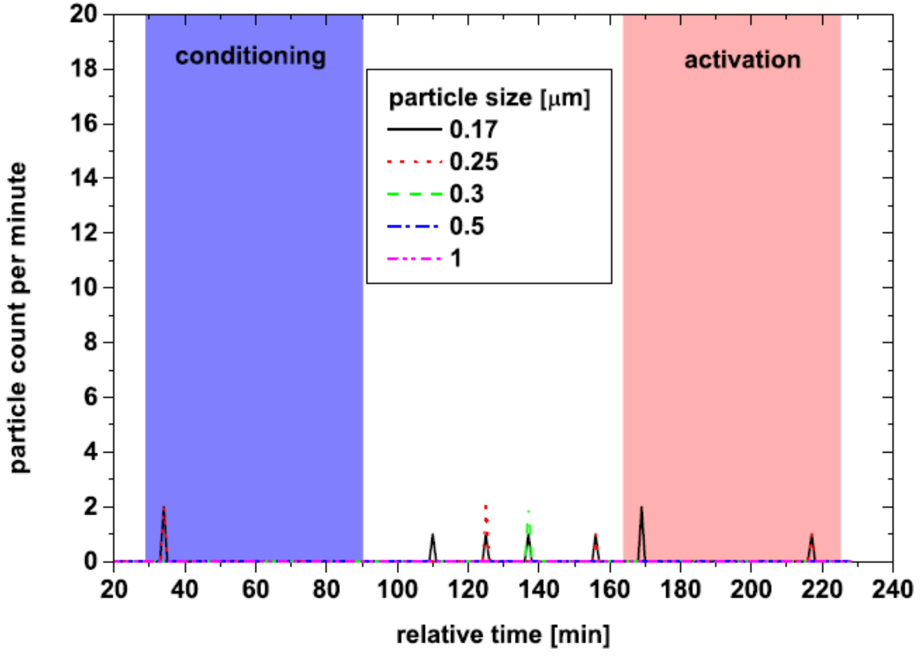


S. Lederer et al., *Particle generation of Capacitorr® pumps*, IPAC 2017

St172™ particle tests in vacuum (DESY): results

After a proper treatment on the pump, the measured numbers are in the order of the detector noise.



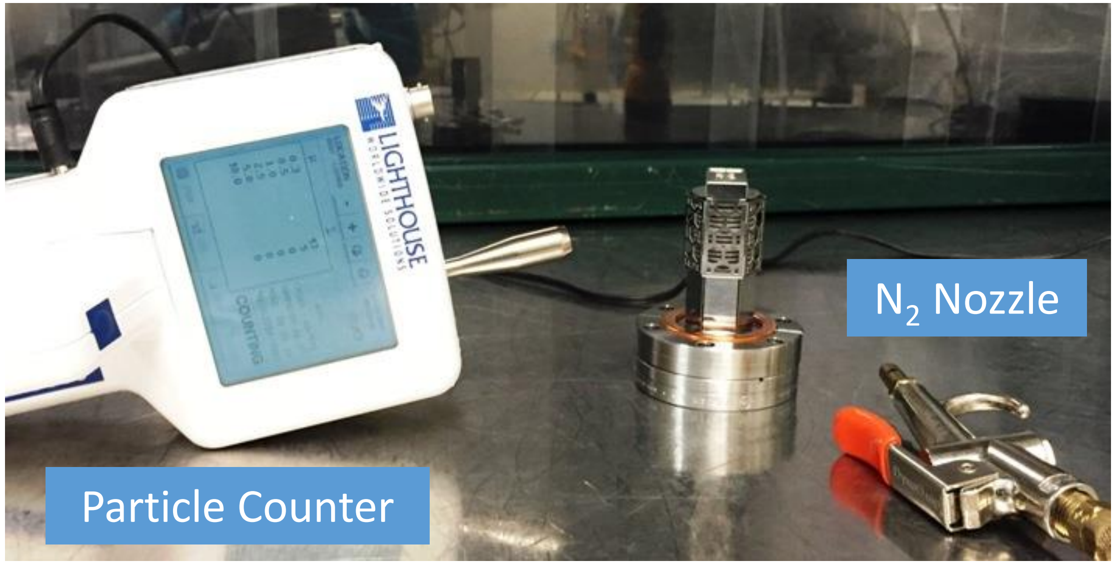


NEG pumps based on St172™ can be properly conditioned for usability in particle-free systems

S. Lederer et al., *Particle generation of Capacitorr® pumps*, IPAC 2017

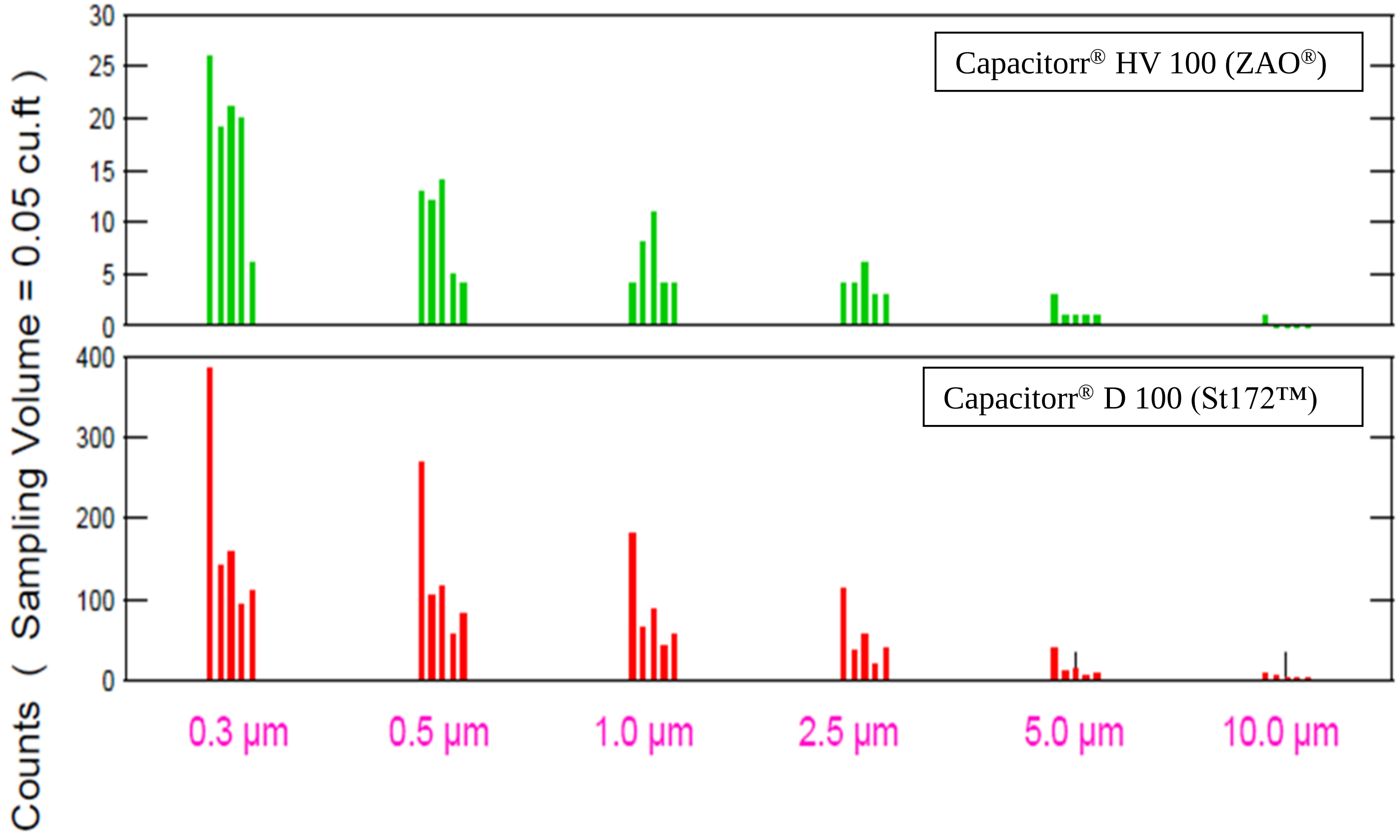
St172™ vs ZAO®: tests at Wilson Laboratory , Cornell

- A comparison between St172™ and ZAO® sintered disks was carried out at Cornell.
- A Capacitorr® D100 (St 172™) and a Capacitorr® HV 100 (ZAO®) went through multiple activation/saturation (with CO) cycles during the vacuum pumping tests and were particle tested immediately after removal from the vacuum test setup.
- The particle tests were done in a clean hood, by blowing clean nitrogen around the pumps.
- A background particle count was measured with N_2 blowing, and showed very low particle counts.
- All pump particle counts were done with 30-sec sampling time, with a sampling volume of ~ 0.050 ft^3.



Courtesy of Yulin Li, Cornell

St172™ vs ZAO®: tests at Wilson Laboratory , Cornell



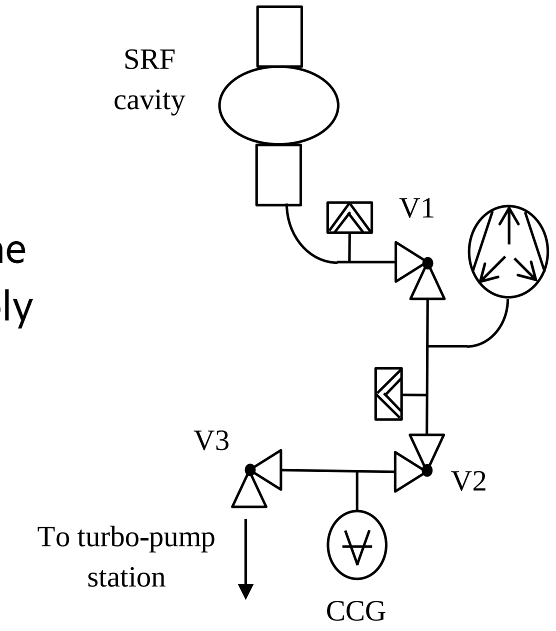
These results show that both alloys can be conditioned and that ZAO® is cleaner than St 172™. Based on these finding, a ZAO® based pump was installed at Cornell close to a SRF cavity with very good results.

Courtesy of Yulin Li, Cornell

ZAO® HV: tests in a SRF cavity (Jlab, USA)

- A Capacitorr® HV 200 (ZAO®) pump was tested at JLab to check for compatibility with high gradient SRF.
- 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.

Schematic of the vacuum circuit attached to the single cell cavity (a) and picture of the assembly hanging from a test stand (b).



(a)

(b)

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

ZAO® HV: tests in a SRF cavity (Jlab, USA)

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

- 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.
- No performance degradation, in terms of field emission onset, resulted from the activation and operation of the pump to an accelerating gradient of 34 MV/m, corresponding to a peak surface electric field of 63 MV/m.

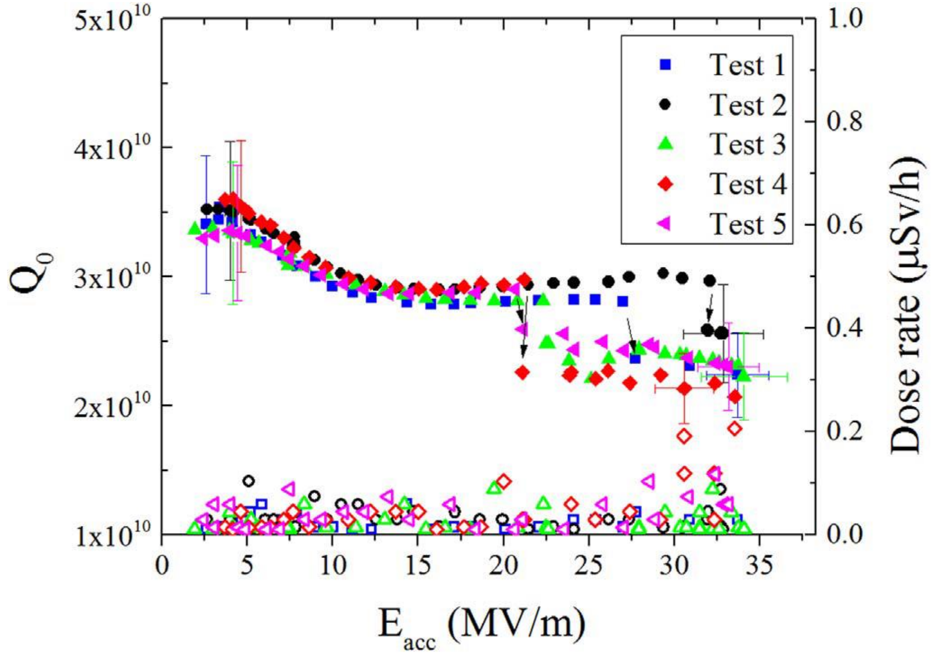
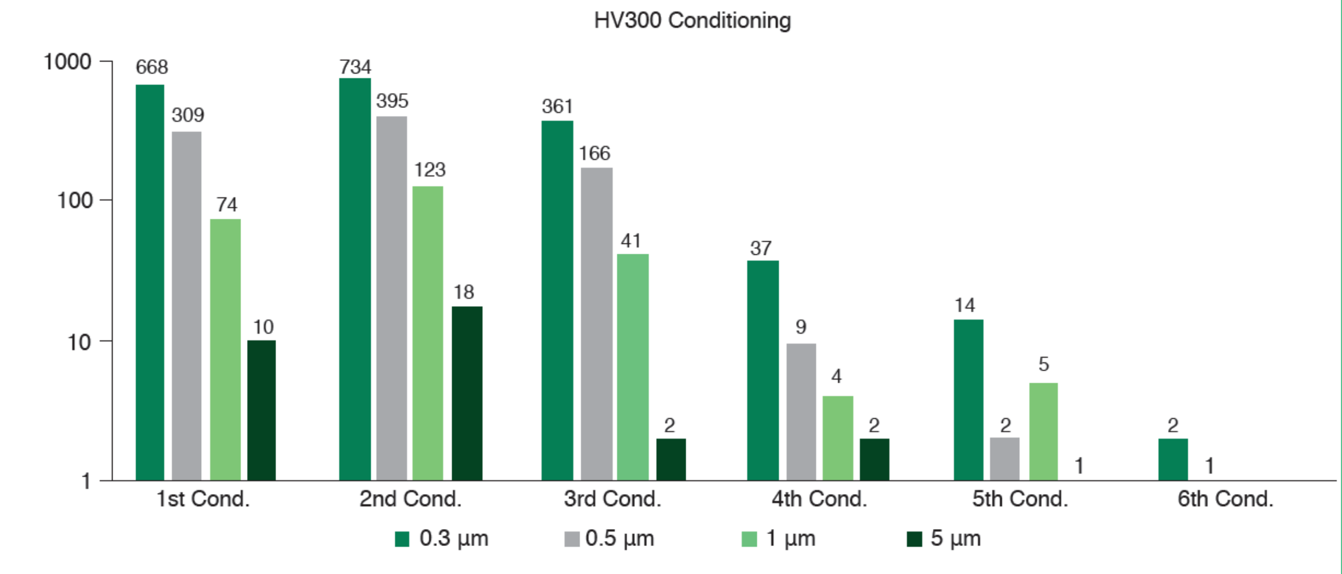


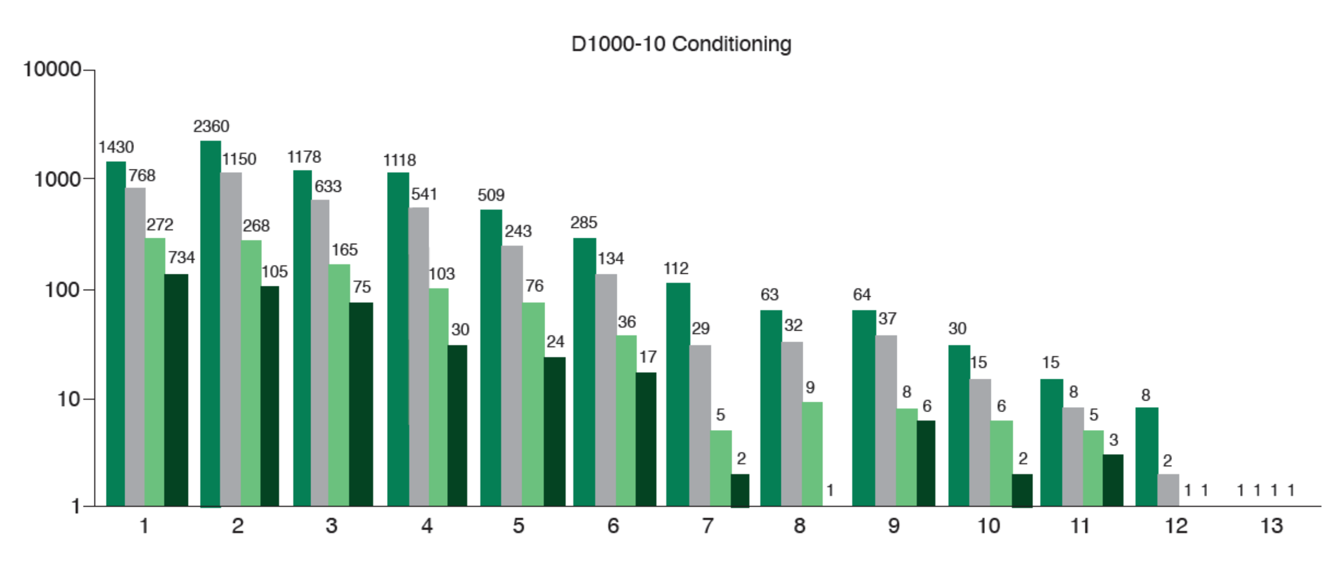
Fig. 3. Q_0 vs. E_{acc} (solid symbols) and x-rays dose rate vs. E_{acc} (empty symbols) measured at 2 K for the 1.3 GHz single-cell cavity with the NEG pump. Please refer to the text and Table 2 for evacuation procedures and pump operation before each test. The dose rate threshold corresponding to the onset of field emission is 0.3 μSv/h. The drop of Q_0 between 20–30 MV/m during all the tests resulted from the processing of multi-pacting.

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

NEXTorr® HV 300 and D1000-10: Jarrige-Ravelli (European Spallation Source)

- **NEXTorr® D1000-10 (St172™) and HV300 (ZAO®)** have been tested to check compatibility with the machine.
- **ESS acceptance criteria**: at most 10 particles in the 0.3 to < 5 µm range and no particles larger than 5 µm after 1 minute of ionized and filtered nitorogen gas throughput at 3 bars, 28 l/min capacity.
- **Conditioning tests** show that 6 and 13 blowing treatments for HV300 and D1000 respectively are sufficient to meet ESS acceptance criteria.

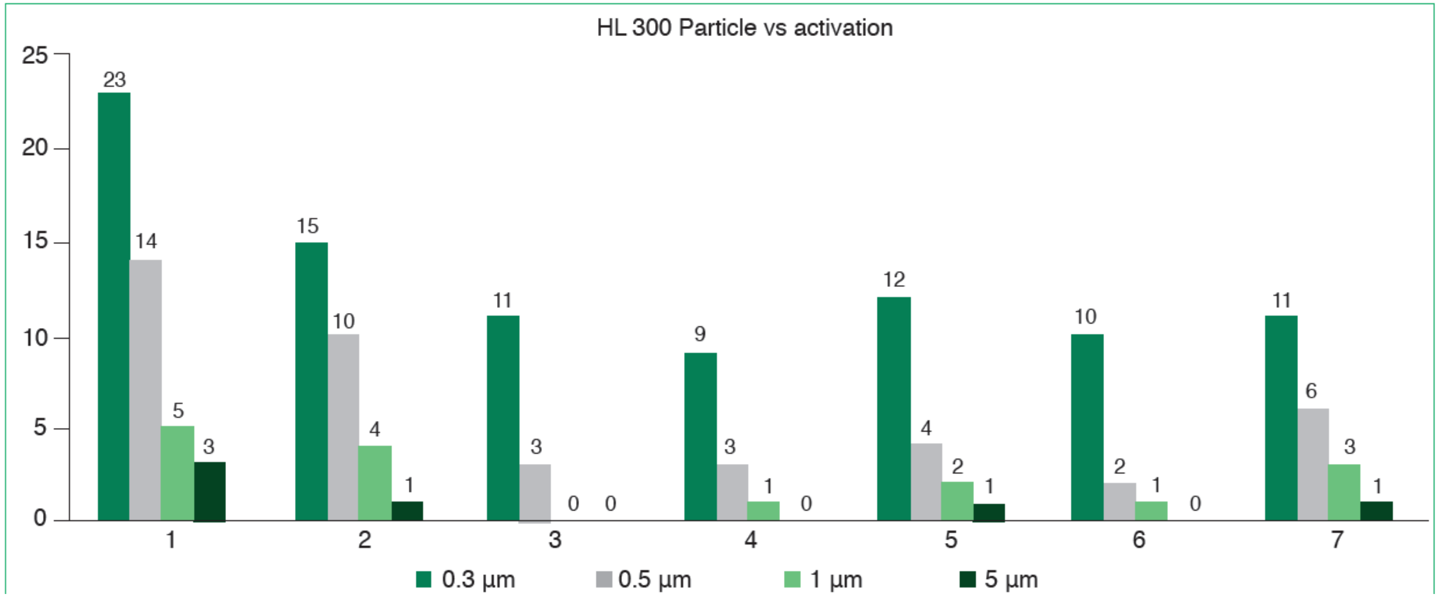


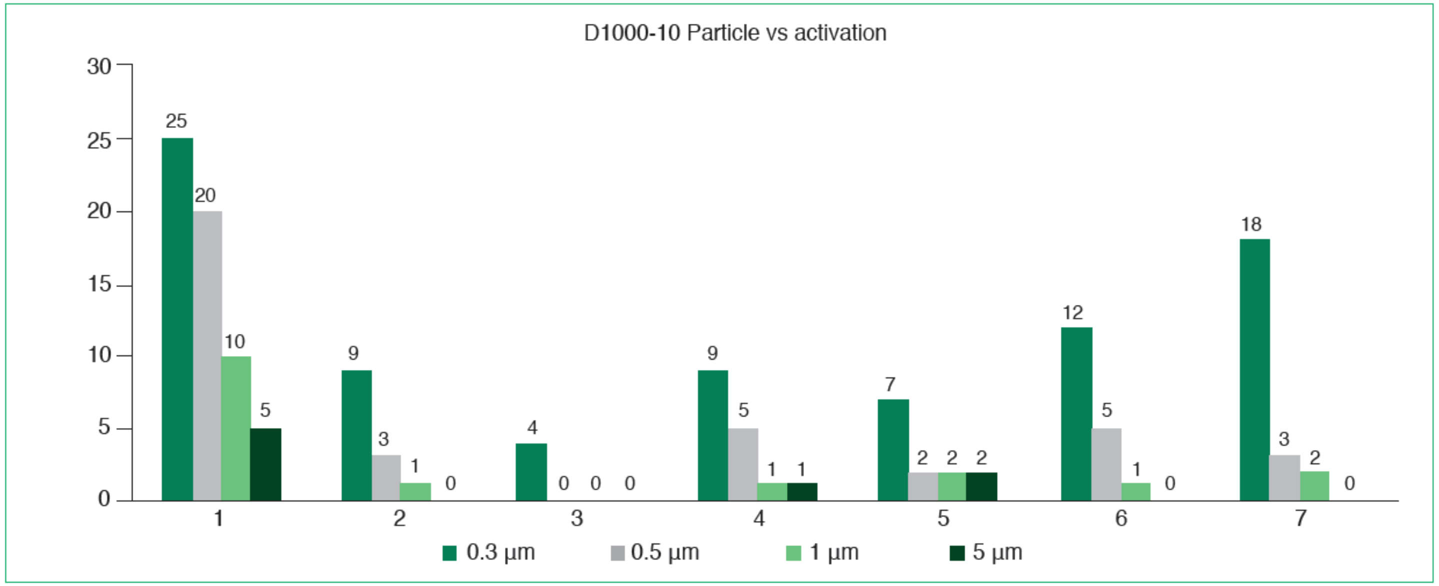


C. Jarrige et al., *Developing the Particle Free Vacuum System at ESS*, Rev. Bras. Apl. Vac., Campinas, Vol. 37, N°3, pp 156-162, 2018

NEXTorr® HV 300 and D1000-10: Jarrige-Ravelli (European Spallation Source)

- **After 7 activations** particle test results demonstrate that pumps are qualified.
- SAES® getter pumps installed on the machine have been particle tested and fulfill ESS requirements.
- Testing indicates that the quantity of particles released fulfills **ISO class 5 standard.**

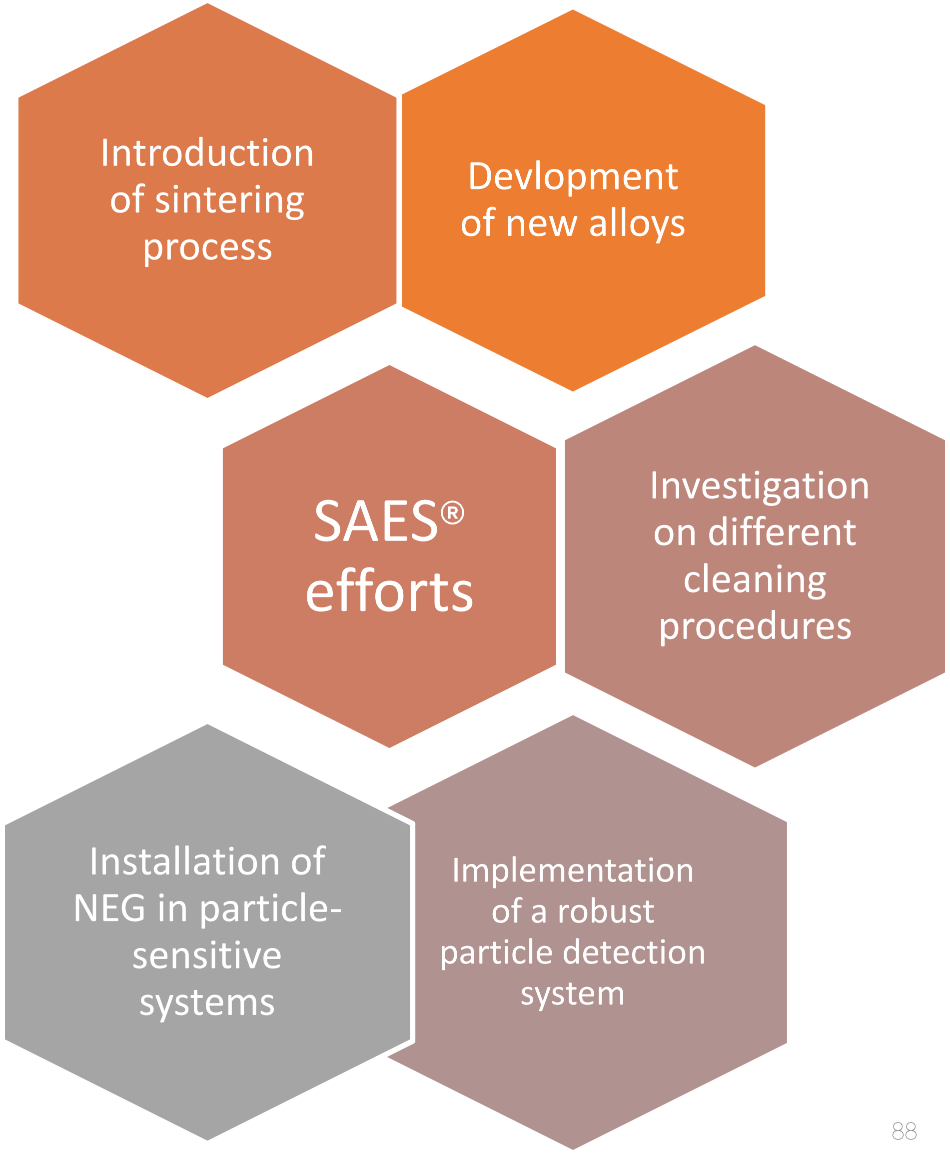




C. Jarrige et al., *Developing the Particle Free Vacuum System at ESS*, Rev. Bras. Apl. Vac., Campinas, Vol. 37, N°3, pp 156-162, 2018

Compatibility of NEG pumps with particle-sensitive systems: SAES® efforts across the years

- SAES® research activities have always been oriented in making getter pumps the solution to more and more demanding particle-sensitive applications.
- SAES® High Vacuum Division across the years tested different methods for particle detection, from dipping to blowing. Both methods have shown that compressed disks release more particles than sintered ones.
- There is not a standard particle counting procedure shared by the scientific community.
- An experimental campaign in SAES® HVD was carried in 2021 with the aim of setting a new procedure for particle counting, with a focus on ZAO® UHV disks, in a ISO 6 cleanroom.



SAES® HVD particle detection system

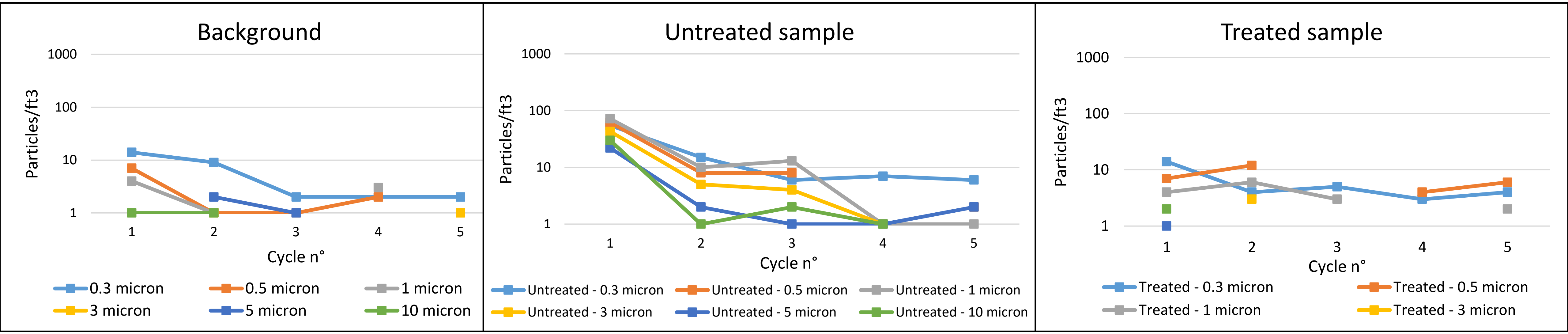
- A robust **particle-detection system** has been implemented in order to collect reliable data on particle release and minimize background effects.
- Ionized and filtered nitrogen is blown on the continuously rotating sample.

Particle counter (TSI AeroTrak®) specifications:

> size range 0.3 to 25 µm,
> particle sizes 0.3, 0.5, 1, 3, 5, and 10 µm,
> counting efficiency 50% at 0.3 µm (100% >0.45),
> concentration limit $4{\cdot}10^5$ particles/ft^3,
> flow rate 28.3 l/min (*i.e.*, 1 ft^3/min)

SAES® HVD particle detection system

- Different pump-cleaning procedures were investigated and the detection system allowed researchers to select the most effective solution for a deep cleaning of getter pumps (SAES® proprietary information).



- The results of countings made in an ISO 6 cleanroom on ZAO® UHV getter alloy samples of 11-disks stacks show the repeatability of the process and the effectiveness of the investigated treatment.

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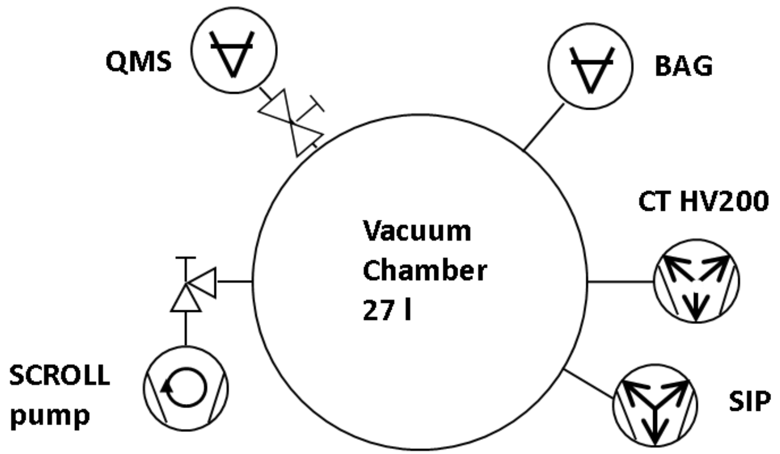
Pump-down with no auxiliary pumps: experimental setup

- Additional series of tests have been performed to demonstrate the feasibility of a pumpdown without the use of a TMP, using only a scroll pump, the CapaciTorr® HV200 and a small SIP.
- The pumpdown has been repeated 30 times to check the pump robustness and possible performance degradation.



Equipment

- SIP noble diode 20l/s
- CapaciTorr® HV200 CF63
- Scroll pump 15 m^3/h
- Full range gauge (pirani+penning)
- BAG

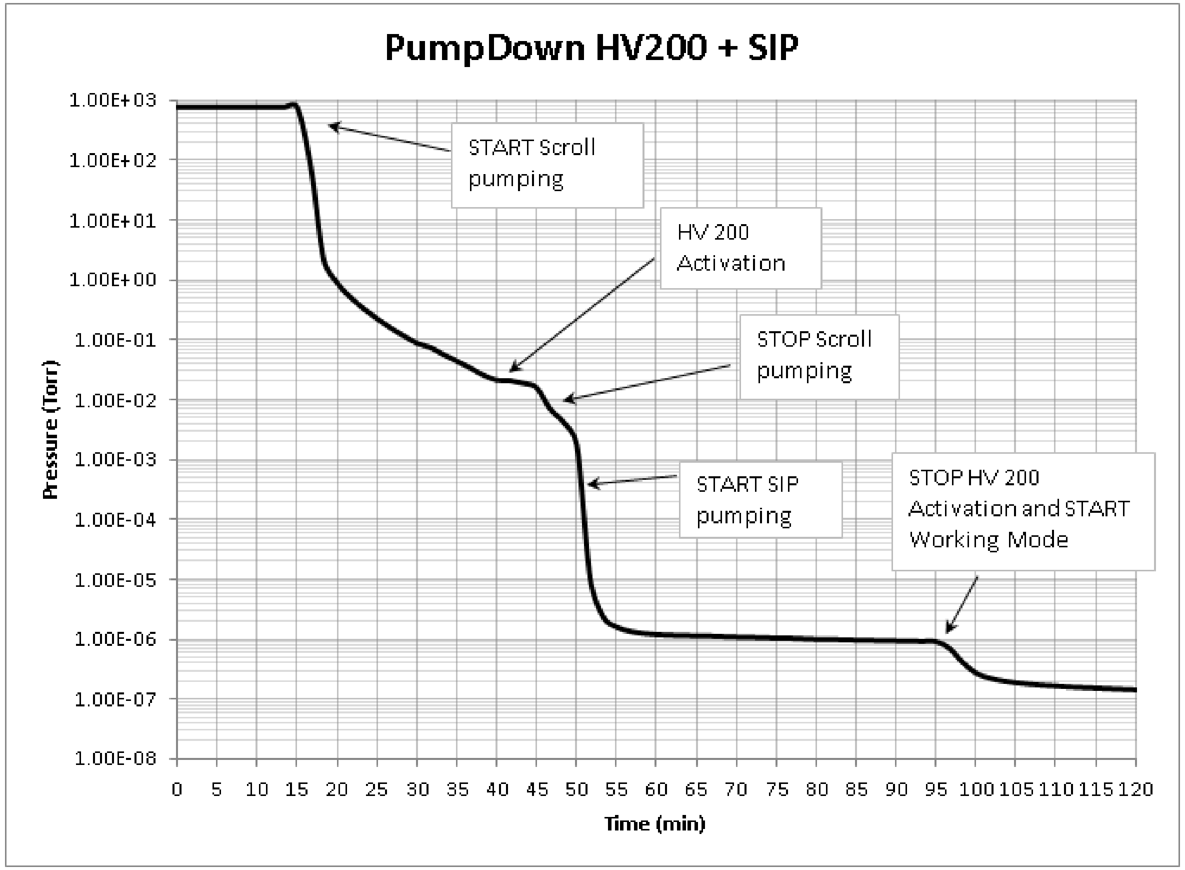
Procedure

- Venting ambient air 16 h
- Pumpdown with scroll pump to 3e-2 Torr
- Start NEG activation 1h
- Isolate scroll at 9e-3 Torr
- Turn SIP ON at 4e-4 Torr
- At the end of activation bring the NEG at HV working temperature (~230°C)

Pump-down with no auxiliary pumps: results

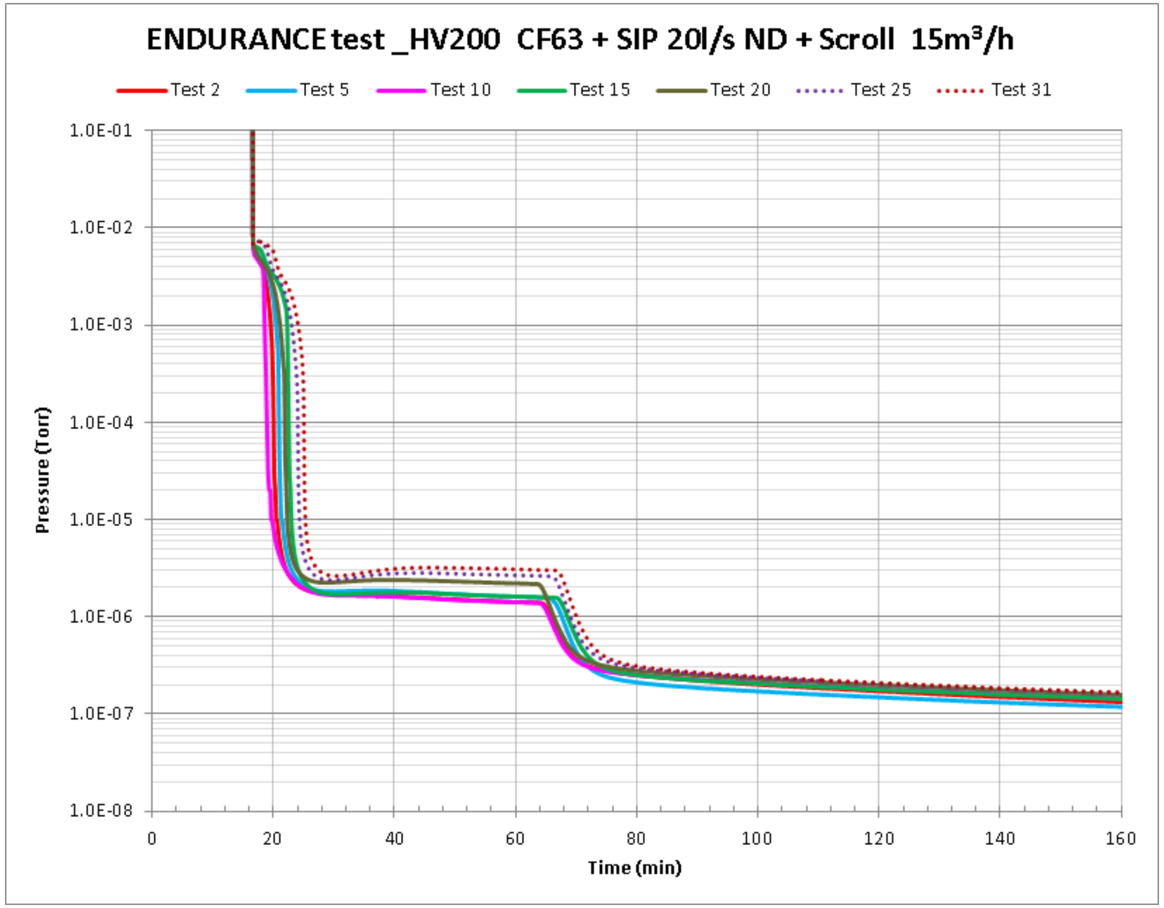
Pressure evolution read by the full-range gauge

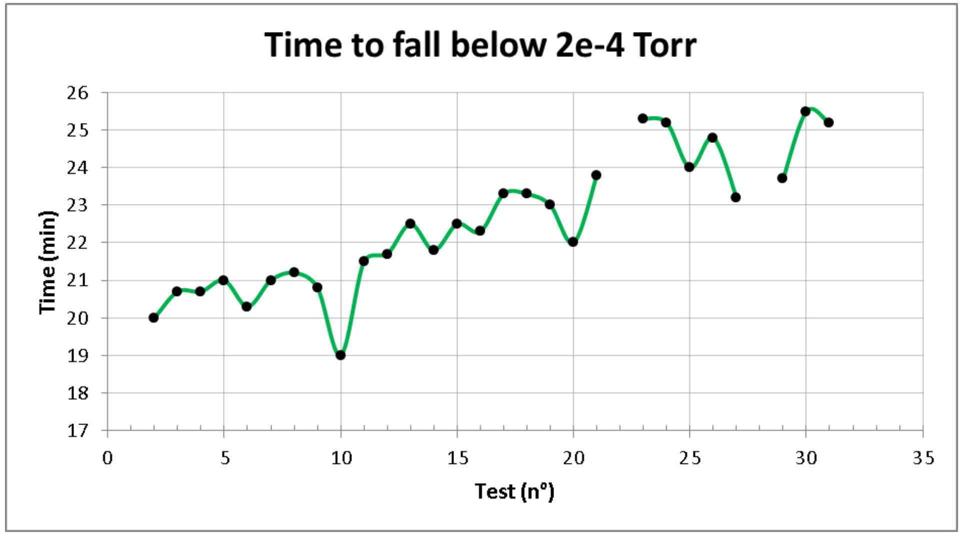
- About 25 minutes are necessary to reach 2e-2 Torr: this time depends on the actual mounting configuration of the scroll pump and its throughput
- About 85 minutes are required to reach the low 10^{-7} Torr vacuum level



Pump-down with no auxiliary pumps: endurance test

- The pump-down process was repeated several times (31 cycles) to investigate possible performance degradation and heater drift
- The pressure evolution after activation is very similar, within about 50%





- The time needed to reach 2e-4 Torr (SIP turned ON) shows a progressive but slow increase.
- About 5 minutes from the first to the last cycles.

Use of NEG pumps in UHV-XHV systems

In the industry

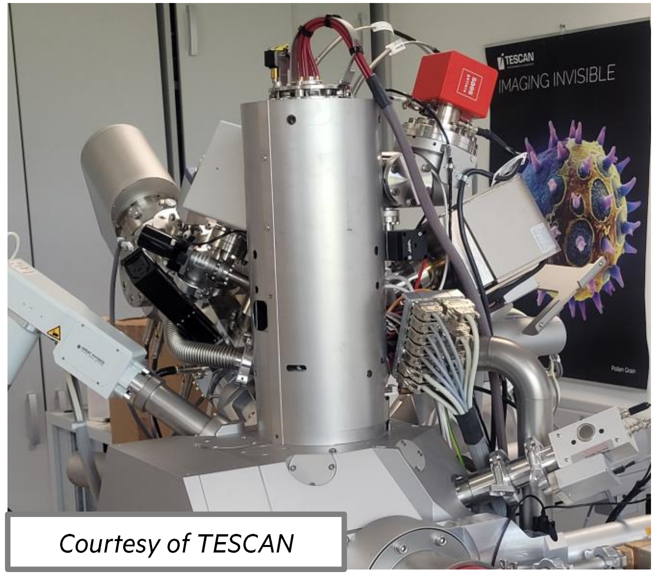
- Scanning/Transmission electron microscopes
- Portable mass spectrometers
- Semiconductor lithographic & metrological tools
- X-ray inspection equipment, EDX analyzers ……

In large physics projects

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

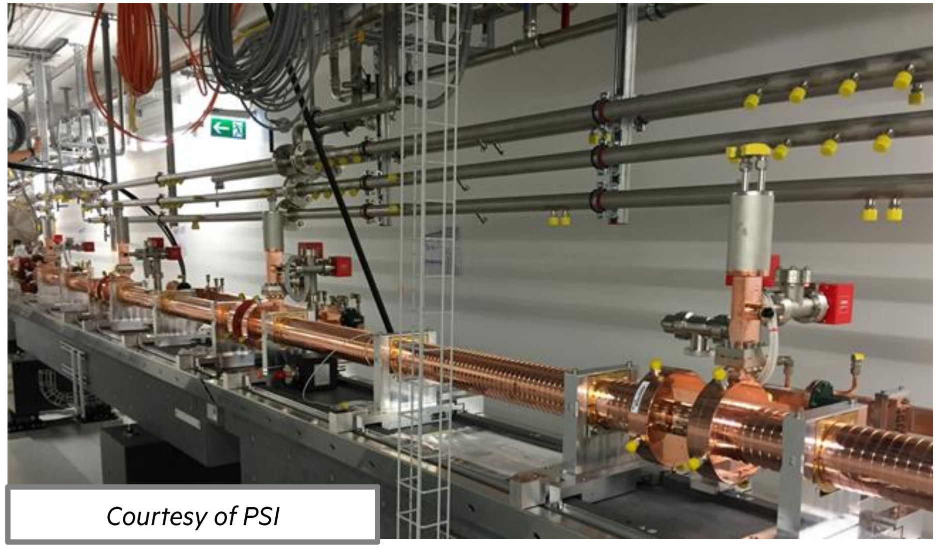
In Scientific Laboratories

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



Courtesy of TESCAN


Portable Mass Spec HAPSITE GC-MS, Courtesy of INFICON


Courtesy of PSI

NEXTORR® Z in E-BEAM UHV GUNS

Only 2.2 Kg pump weight

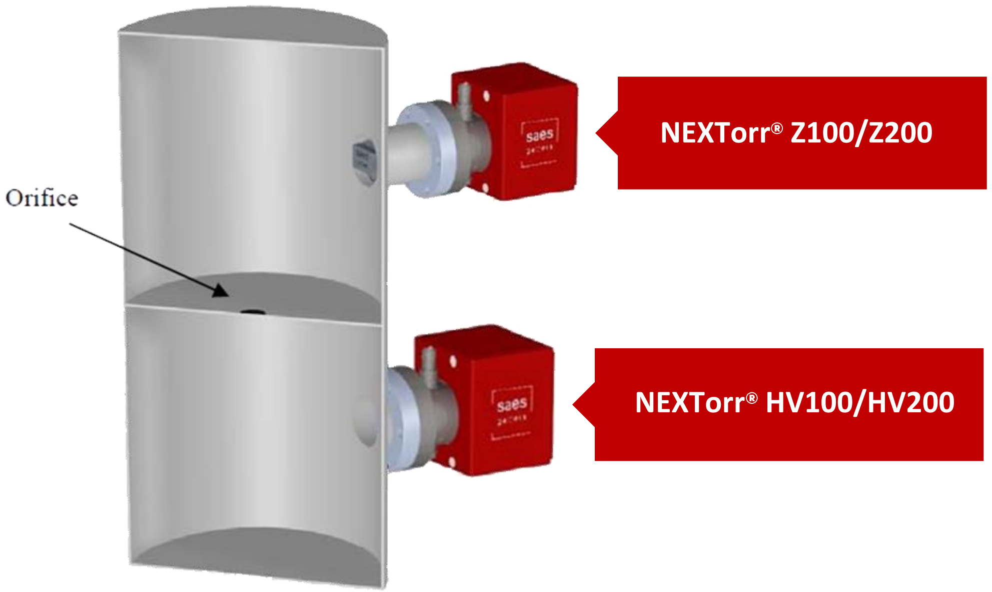
- easy to handle and to install
- no vibrations

High pumping rate for H_2 and all gas species

- lower bottom pressure
- high brightness source
- longer source lifetime

The NEXTorr® keeps pumping without power

- transport the column in vacuum
- no need to bake again the gun at user site
- faster system installation
- quick recovery in case of accidental power cutoff



Courtesy of TESCAN

NEXTorr® pumps in RAITH EBPG PLUS

RAITH GROUP, a leading precision technology solution provider for electron beam lithography, has launched its new EBPG Plus e-beam lithography tool incorporating NEXTorr® pumps

Courtesy of RAITH

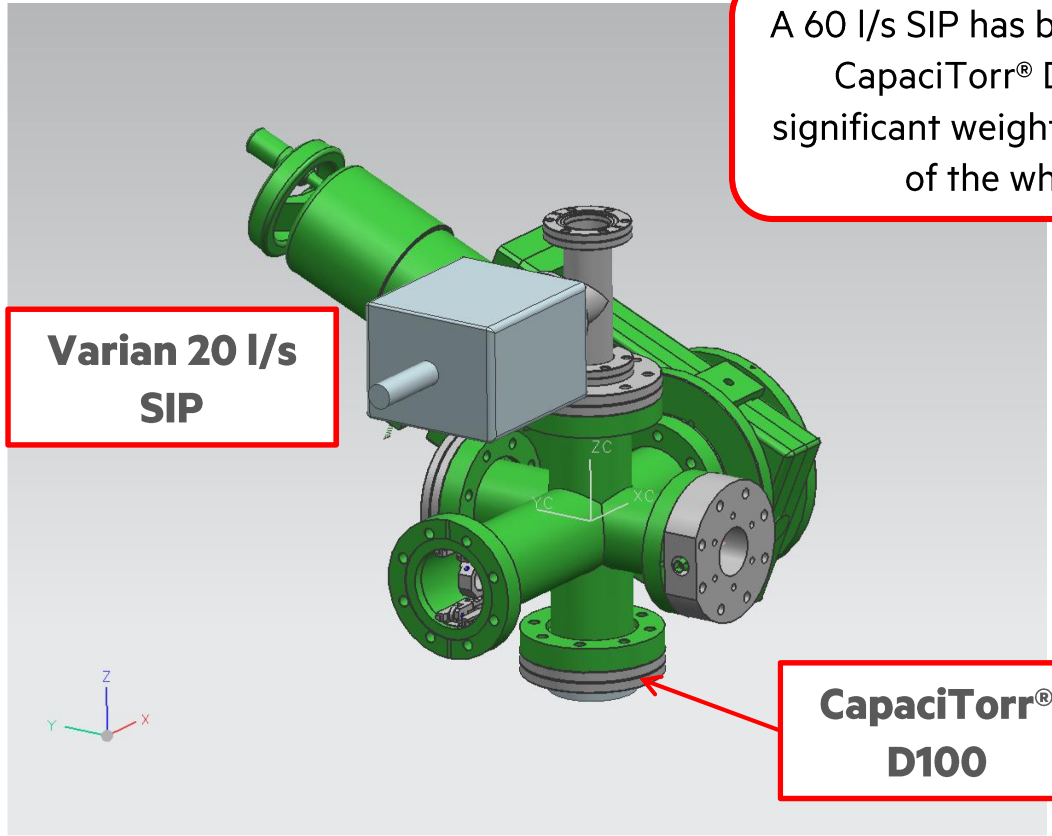
NEXTorr® and CapaciTorr® in UHV suitcases and transfer tools

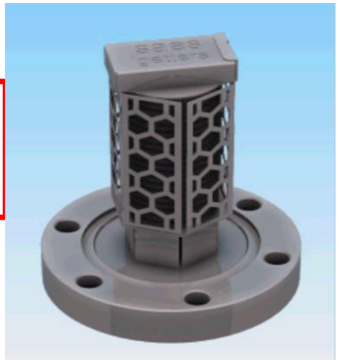
- Results obtained by INFN-LASA replacing a 60 l/s ion pump with a small CapaciTorr® D 100 pump (200 g weight) in a photocathode transportation vessel.

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

- Using the CapaciTorr® D 100, after **3 days** bake-out, a pressure of **2E-11 mbar** was achieved.

- Such pressure could be maintained over one month, even without any power.



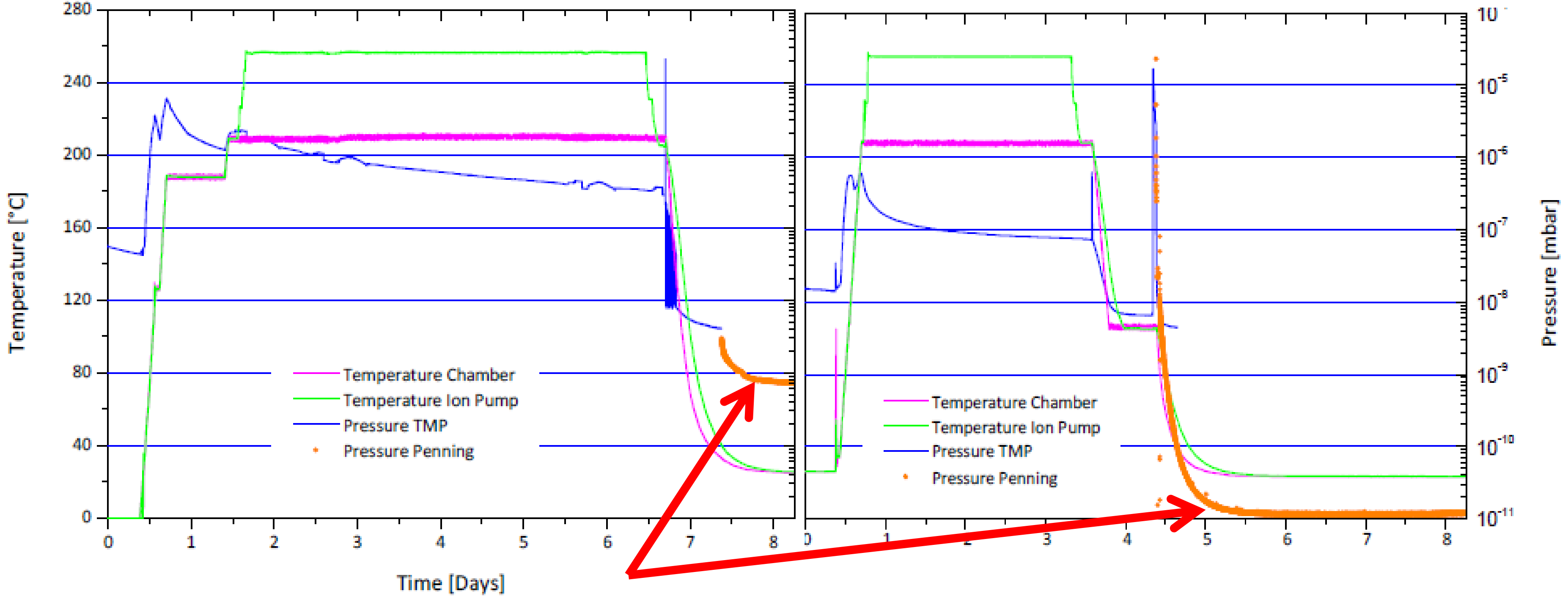


D. Sertore et al., Ultra High Vacuum Transport System for high Quantum Efficiency Photocathodes, proceeding IPAC 2011

NEXTorr® and CapaciTorr® in UHV suitcases and transfer tools

20 l/s + 60 l/s SIP (7 days BO)

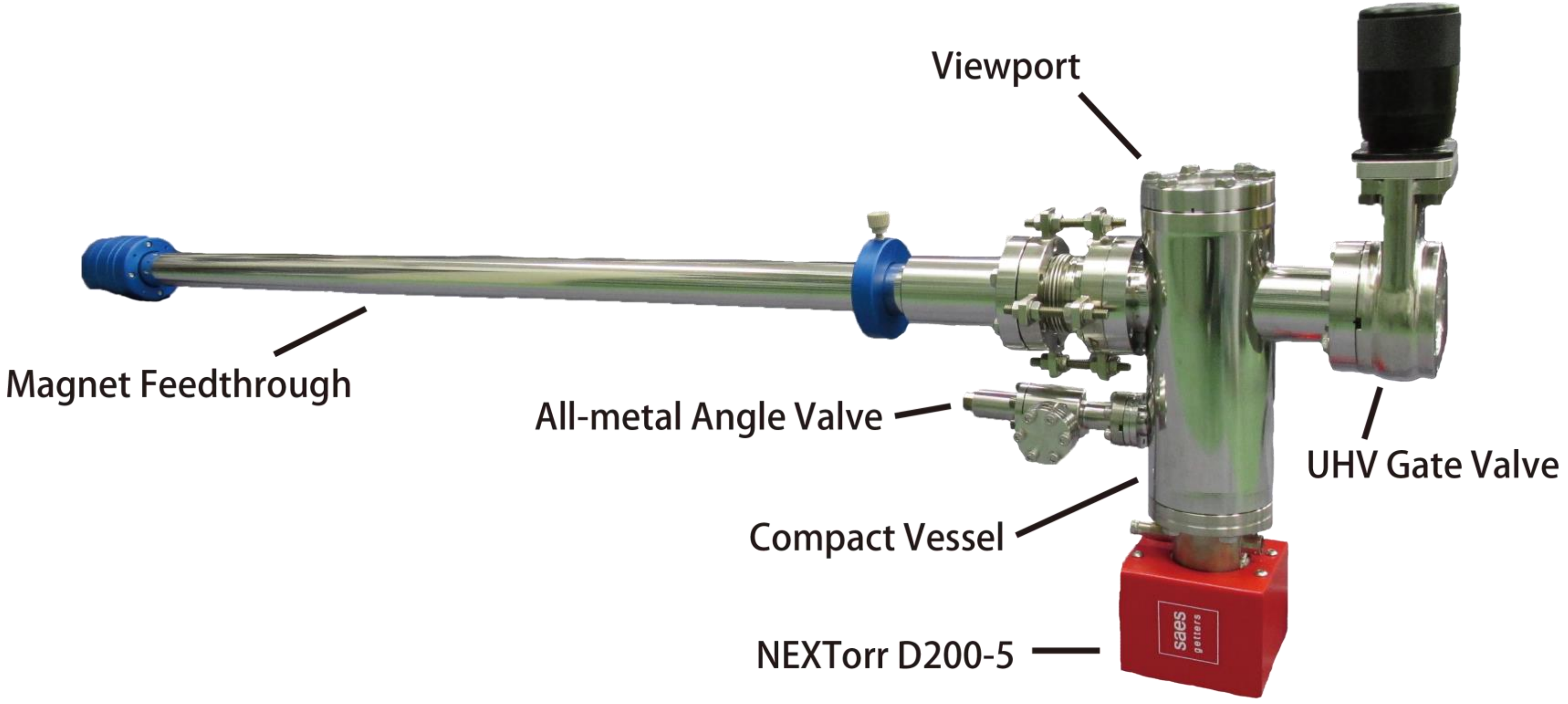
20 l/s + CT D100 (3 days BO)



Vacuum 50 times better achieved in half of the time!

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

NEXTorr® and CapaciTorr® in UHV suitcases and transfer tools



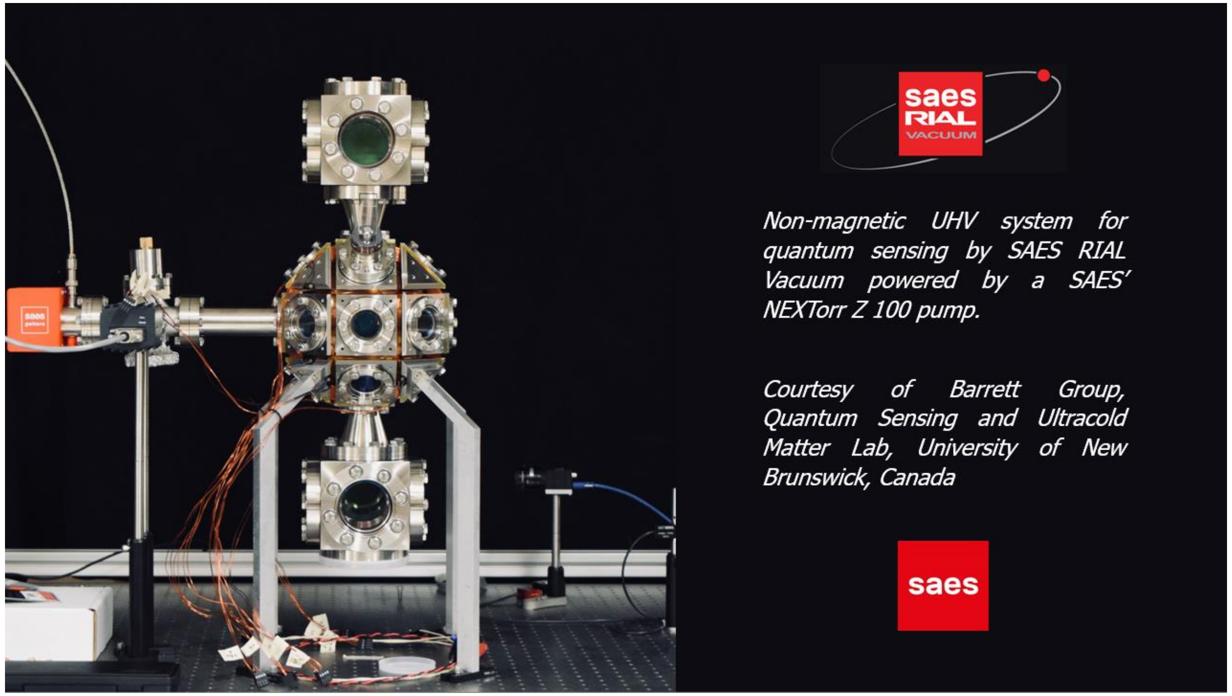
UHV Transfer Vessel

Maintain 1.7×10^{-8}Pa for three days with NEXTorr Ion Pump turned on!
Maintain 1.5×10^{-7}Pa for three days with NEXTorr Ion Pump turned off!

ATV-200/NS/275/800/TEP/
AVC Co,.LTD

Ion trap - quantum computing applications

Courtesy of Mr. Frieder Lindenfelser (group of Prof. Home), ***ETH Zürich***



Quantum Computing systems based on ION TRAPS require:

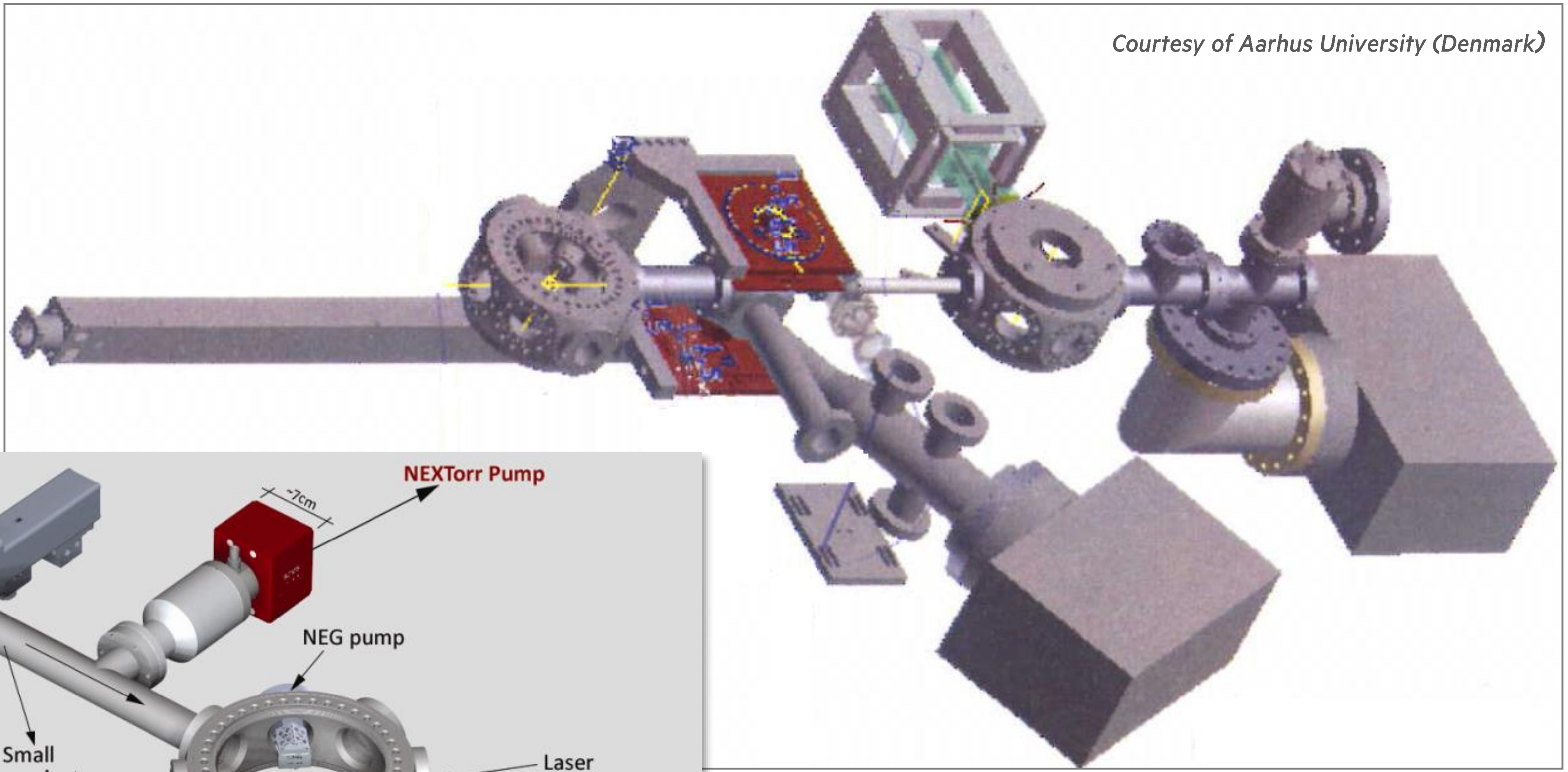
- XHV levels (10^{-12} mbar)
- no vibrations nor magnetic interference
- extreme compactness

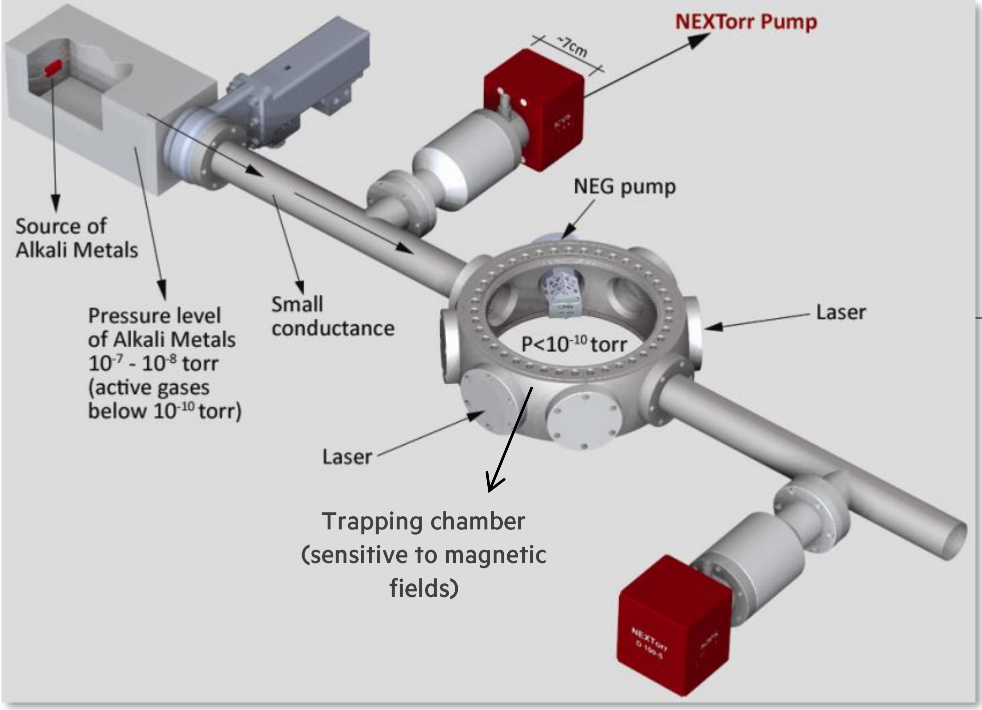
NEXTorr® pumps are the best solution

In few years NEXTorr® has become a benchmark in the field, with impressive design improvements!

Cold traps systems – new design

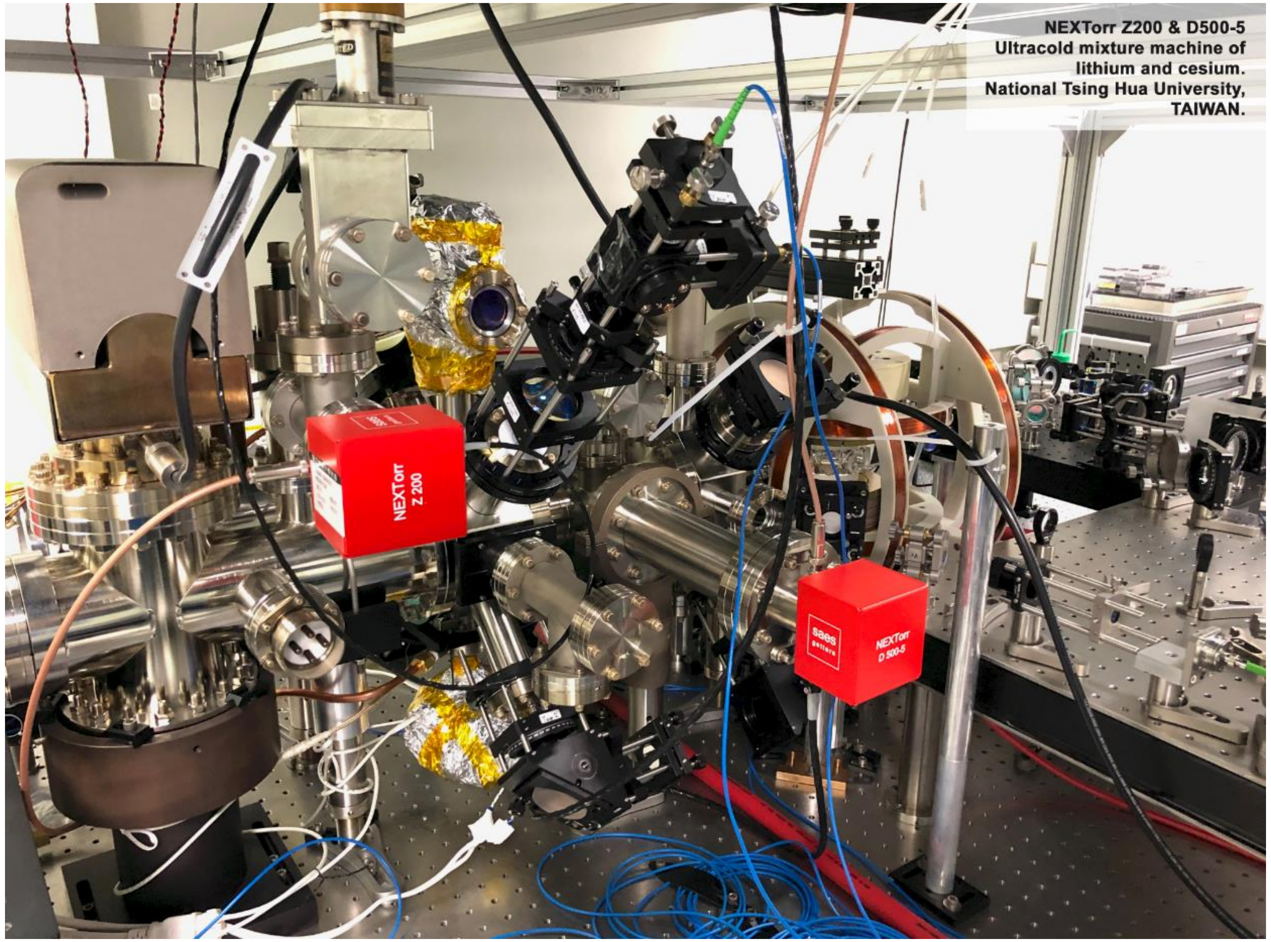
From this....
with bulky SIP far from the chambers



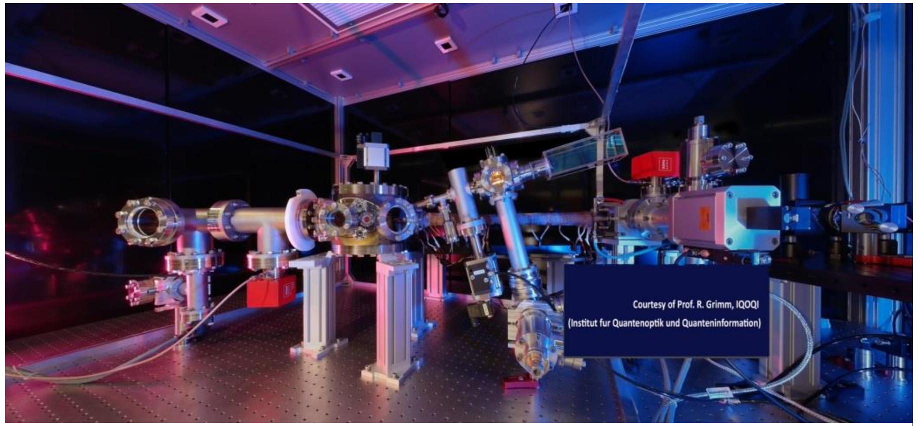


.... to this
with NEXTorr® pumps close or even into the chamber

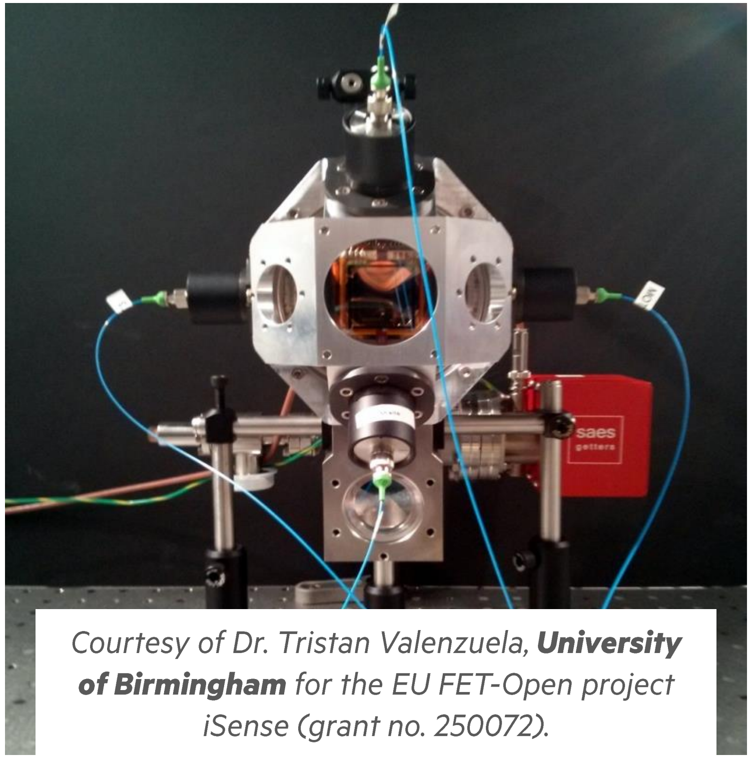
Further examples of NEXTorr® in trapping systems



Li – Cs trapping system with NEXTorr® Z200 and NEXTorr® D500



*Courtesy of Dr. Rudolf Grimm, **University of Innsbruck***



*Courtesy of Dr. Tristan Valenzuela, **University of Birmingham** for the EU FET-Open project iSense (grant no. 250072).*

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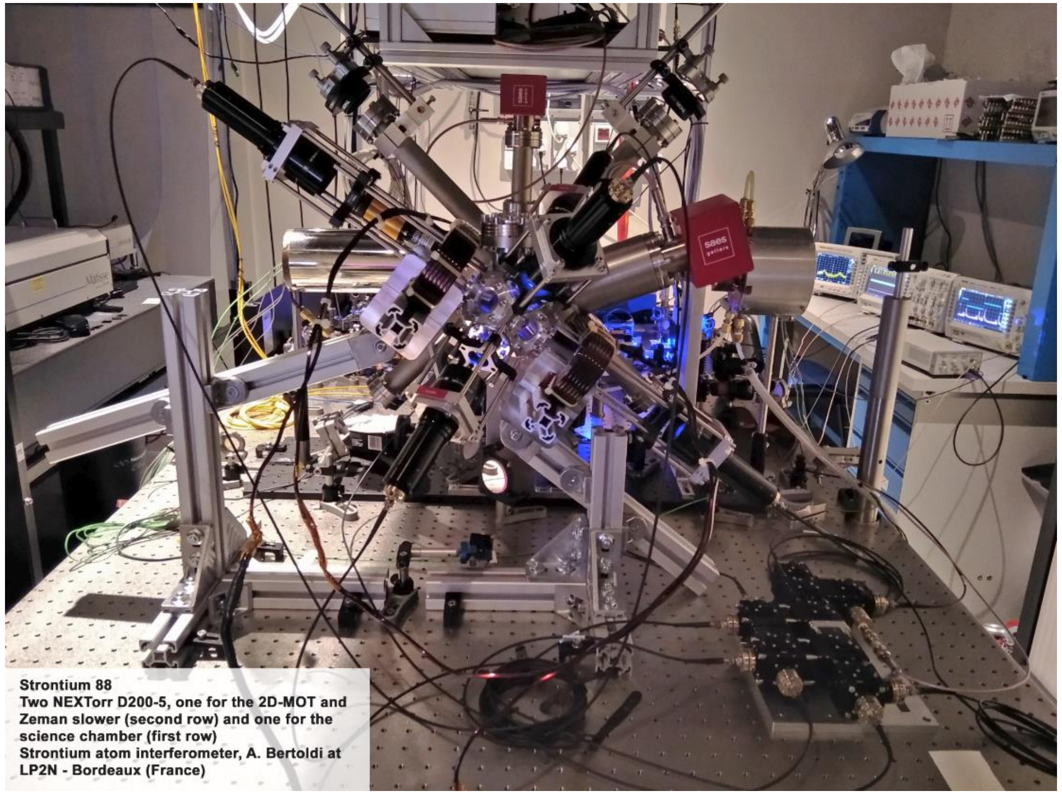
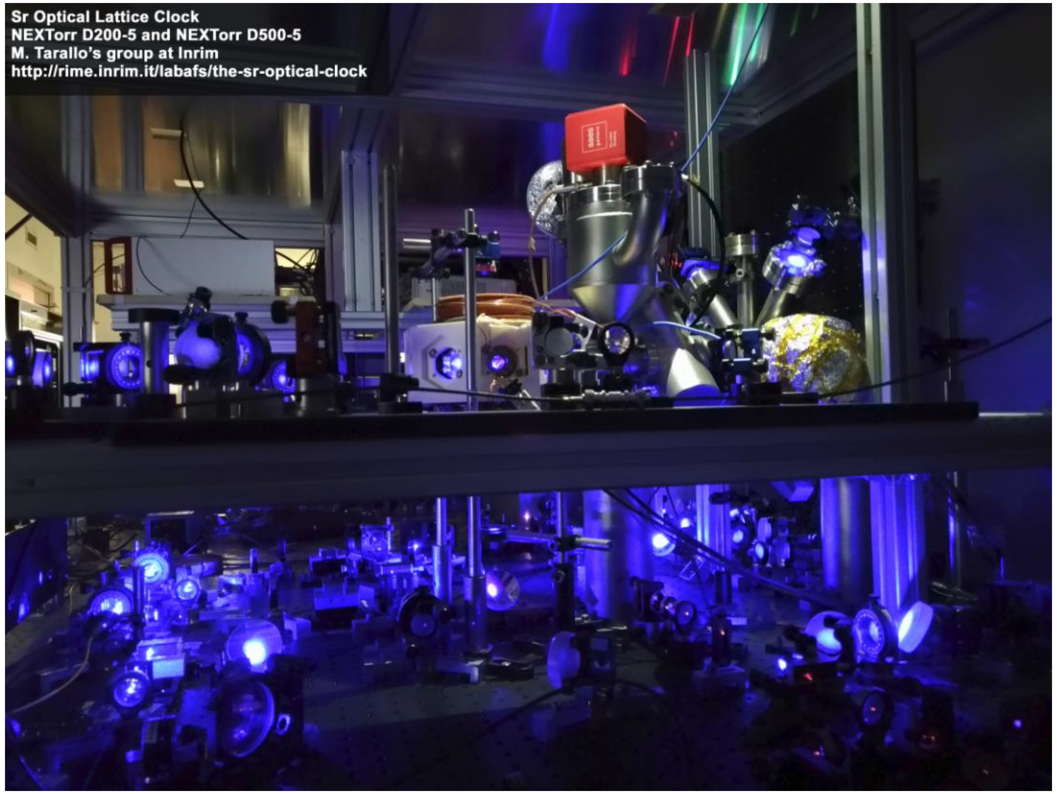
high vacuum

Further examples of NEXTorr® in trapping systems



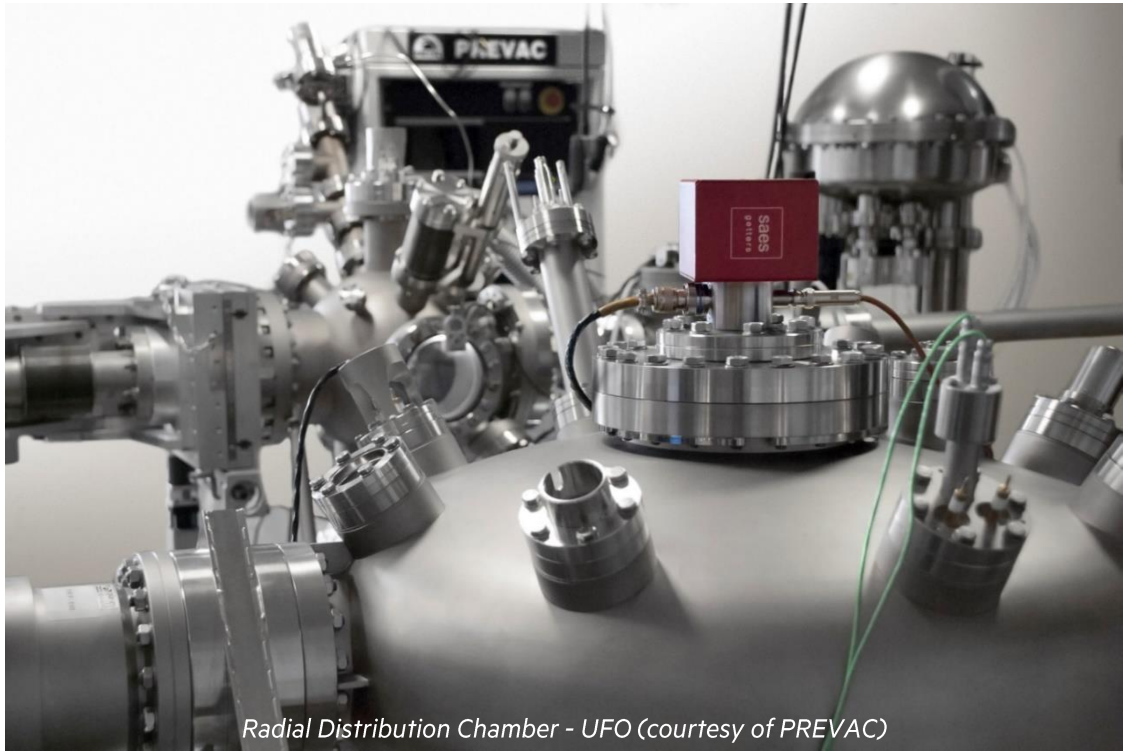
Sr Atom Interferometer with NEXTorr® D200



Sr Clock with NEXTorr® D200 and NEXTorr® D500

NEXTorr® in Surface Science systems

- Extremely compact and light -> easy to handle and to install
- High pumping rate for H_2 and all gas species -> lower bottom pressure
- Keeps pumping **without power** -> quick recovery in case of accidental power cutoff
- No parts in motion -> total absence of any vibrations
- Ideal for STM, SPM, ARPES, AES, XPS, LEEM/PEEM,….



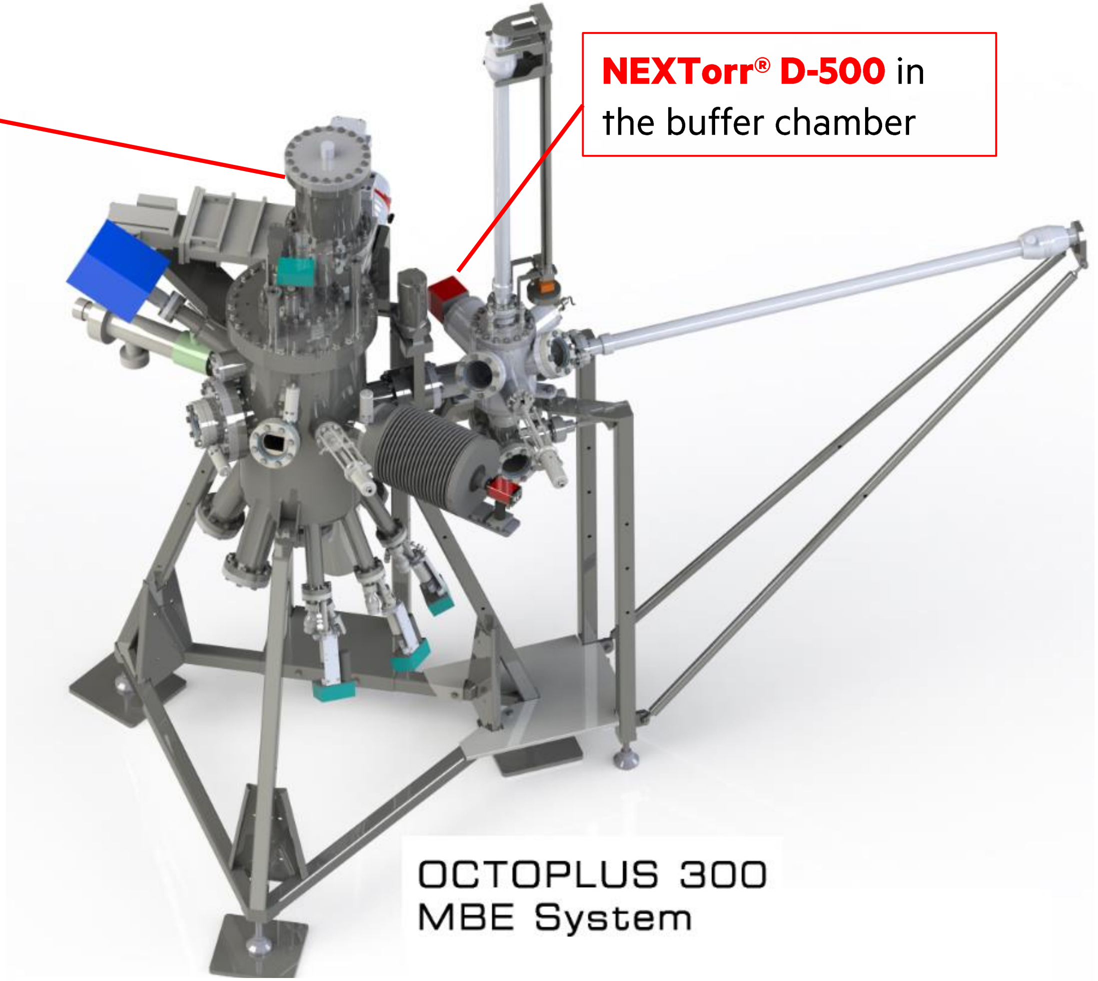
Radial Distribution Chamber - UFO (courtesy of PREVAC)

SAES® NEG pumps in MBE systems (deposition chamber)

CapaciTorr® D 2000 in the main chamber

NEXTorr® D-500 in the buffer chamber

- In a MBE system with cryo-cooled walls during the deposition, a 300 l/s ION pump has been replaced by a **CapaciTorr® D-2000** (CF150 flange), added to a Turbo pump
- Huge pumping speed vs pump size lower bottom pressure for cleaner deposition process
- The NEG pumps without power vacuum is preserved in case of accidental power cutoffs

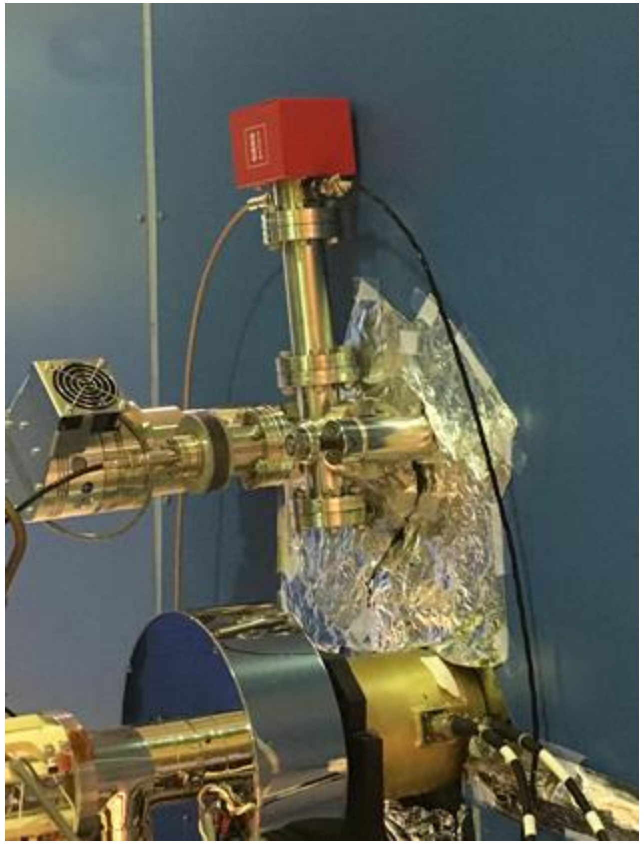


Courtesy of Dr. Eberl MBE-Komponenten GmbH

P in the 10^{-11} mbar before cryo-cooling the chamber walls

Courtesy of Mr. Frank Roesthuis (University of Twente)

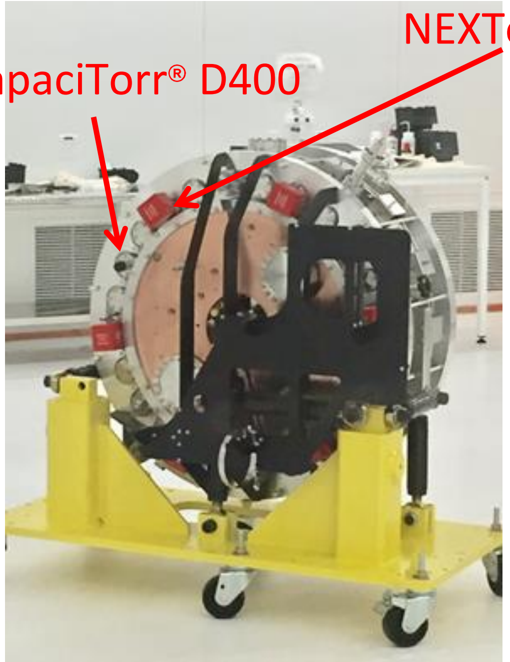
DC electron gun in the X-band cell LINAC at Taiwan Light Source



Courtesy of LINAC Group at NSRRC – Dr. Ching-Lung Chen and Dr. Kuang-Lung Tsai

- NEXTorr® D200-5 has been used
- Pressure 1E-9 Torr
- Using NEXTorr®, lifetime of e-gun is doubled

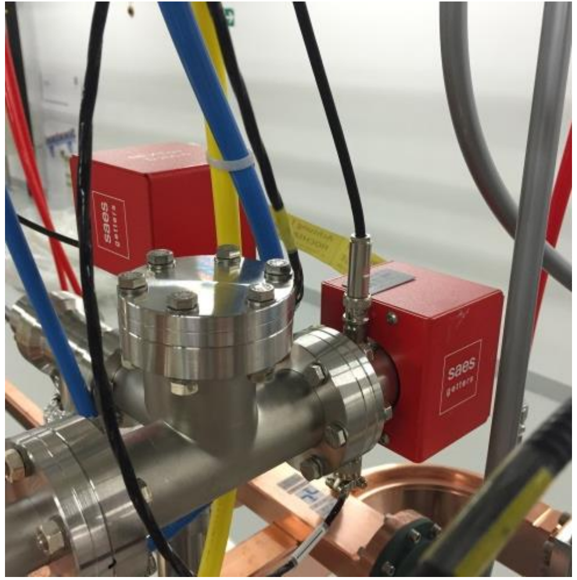
LCLS-II Injector source gun

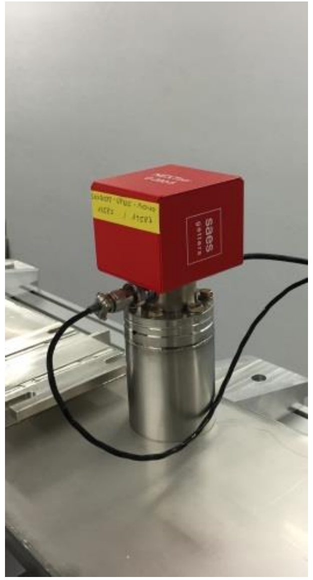


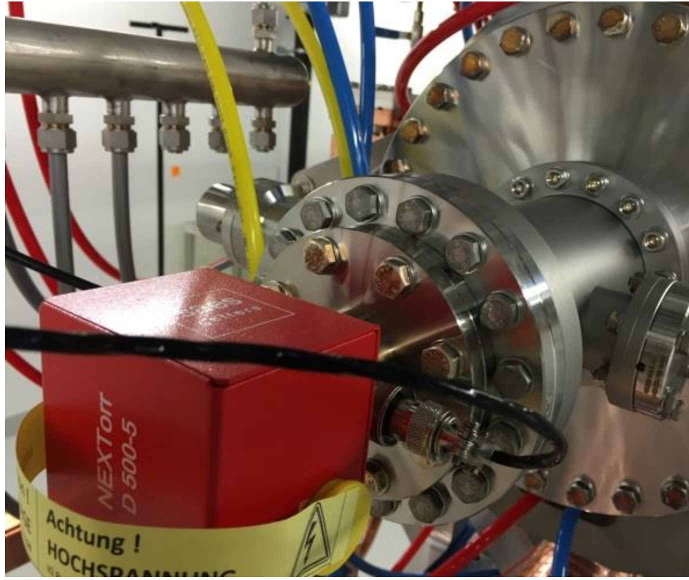
- 6 NEXTorr® D200-5 ND and 6 CapaciTorr® D400 are distributed around the LCLS-II injector source gun
- The pumps have been installed in a class 100 (ISO 5) and 1000 (ISO 6) rated cleanrooms

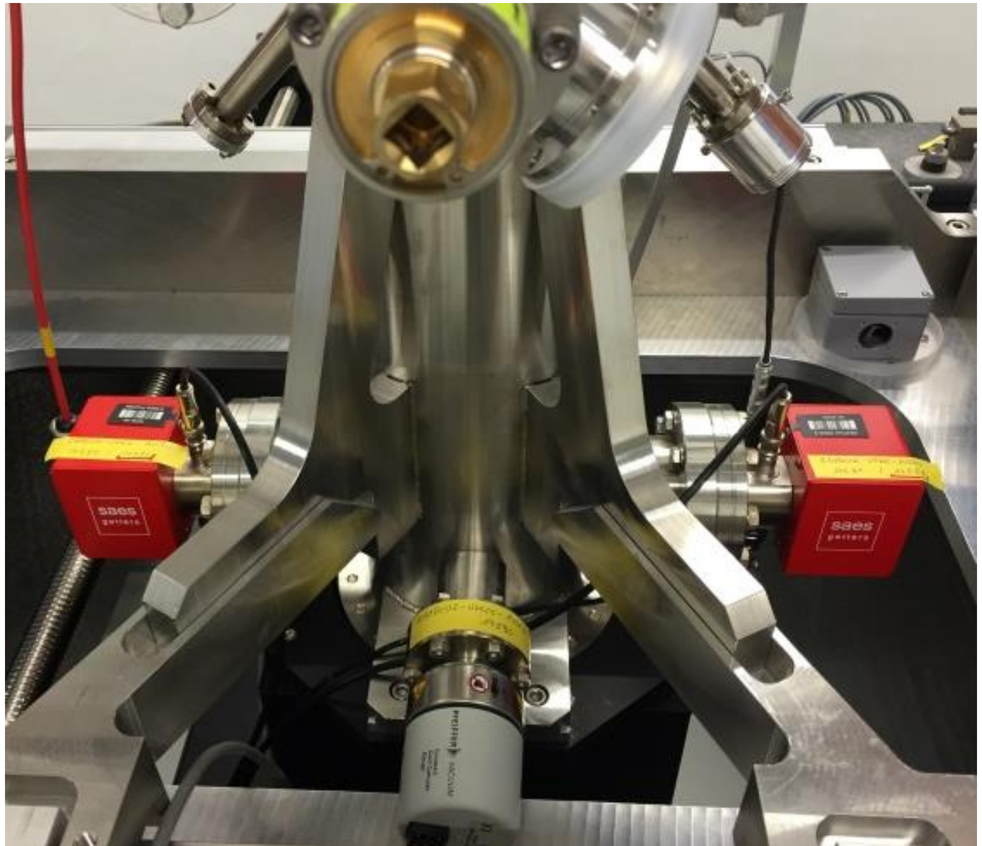
Courtesy of Steve Virostek and Matthew Johnson, Lawrence Berkeley National Laboratory

NEXTorr® in Accelerators: SWISS-FEL Linac



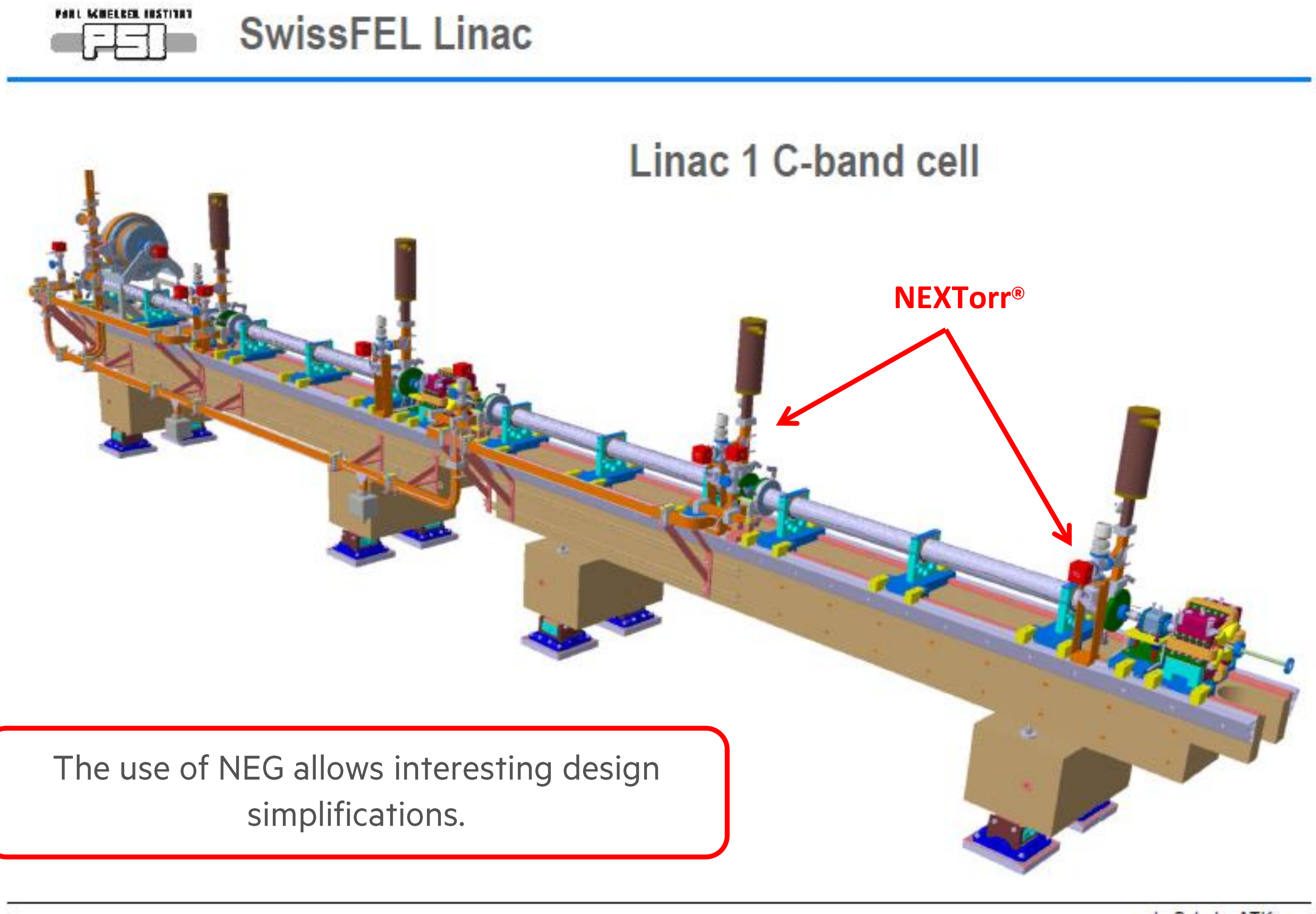






saes high vacuum

NEXTorr® in Accelerators: SWISS-FEL Linac



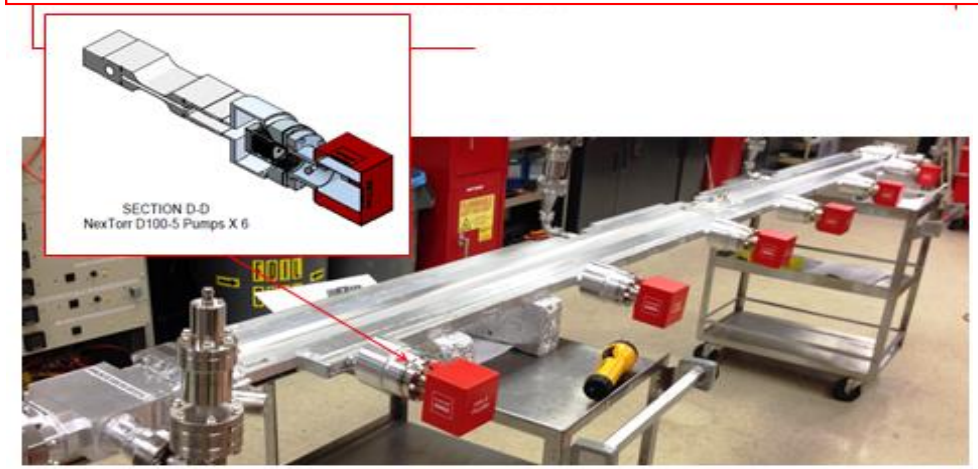
The use of NEG allows interesting design simplifications.

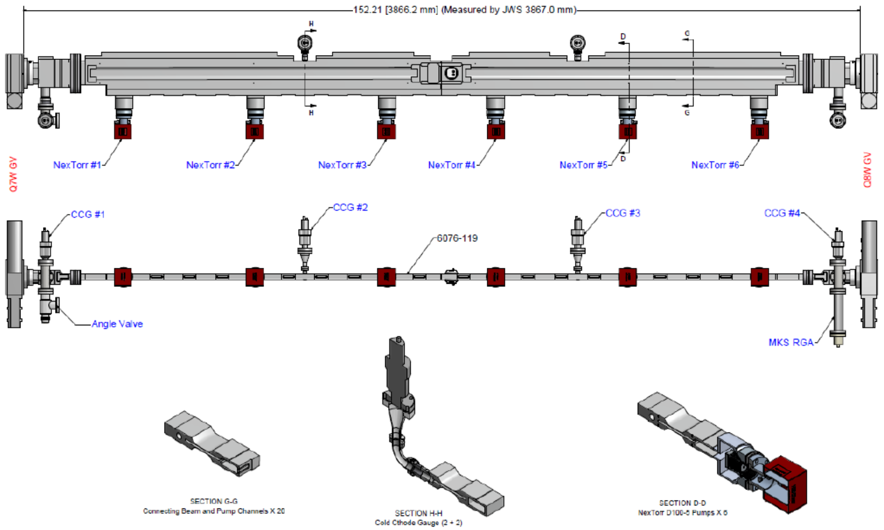
Courtesy of SwissFEL

Undulator vacuum test chamber

- NEXTorr® pumps are distributed along the undulator
- Compared to strip, NEXTorr® distribution could provide easier installation and maintenance
- If issues are generated in the pumping system
  - With strip all the chamber must be uninstalled and changed
  - With NEXTorr® only a 2 kg pump must be replaced

Six NEXTorr® D100-5 Pumps on Undulator Chamber





- This layout allows also the distribution of compact ion elements instead of big Ion pumps at the end of undulator
- The distribution of the ion element through NEXTorr® allows also a distribution of the pressure indication in the undulator to better monitor the pressure evolution during beam circulation and commissioning phase
- The pump is immersed in the high magnetic field close to the in-vacuum undulator (i.e., same plane of the circulating beam)
- Vacuum level 10^{-10} Torr

saes high vacuum

Courtesy of Wilson Lab., Cornell High-Energy Synchrotron Source (CHESS)

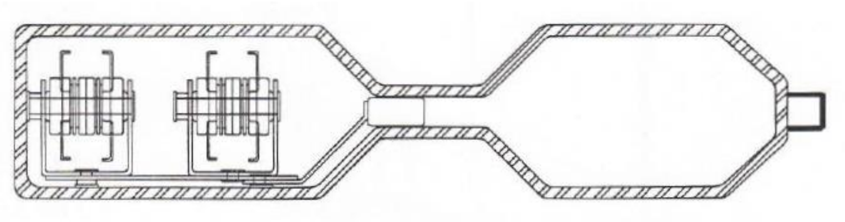
RF cavities - ELETTRA

NEXTorr® D500-5

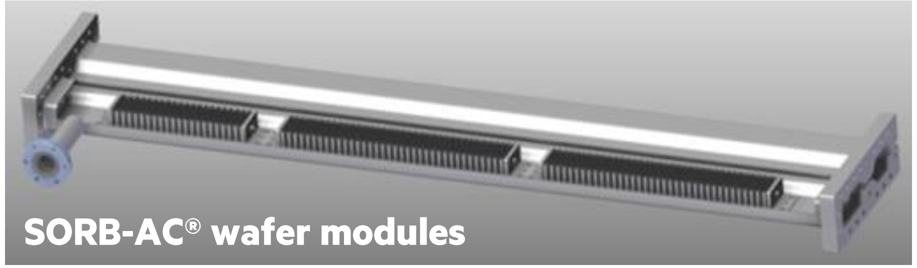
- NEXTorr® has been used in the RF cavity at ELETTRA, Italy, reducing of a factor 4 the pressure compared to a standard ion pump
- The better pressure was achieved because the NEXTorr could be installed close to the cavity without affecting its performances, while the ion pump should be installed far from the cavity, for the interference with the magnetic field generated by the cavity

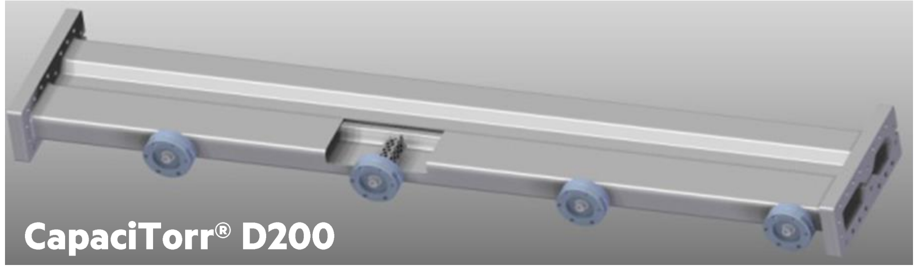
DELTA: distributed vs discrete pumps

- Replacement of St707® NEG strips placed in the antechambers of DELTA storage ring.
- Installation of strips is rather complex (heaters, positioning, space constraints) and it is difficult to achieve full activation.



- Possible alternative solutions for 1.2 m long straight chambers:
  - SORB-AC® NEG wafer modules,
  - CapaciTorr® D200 NEG pumps.

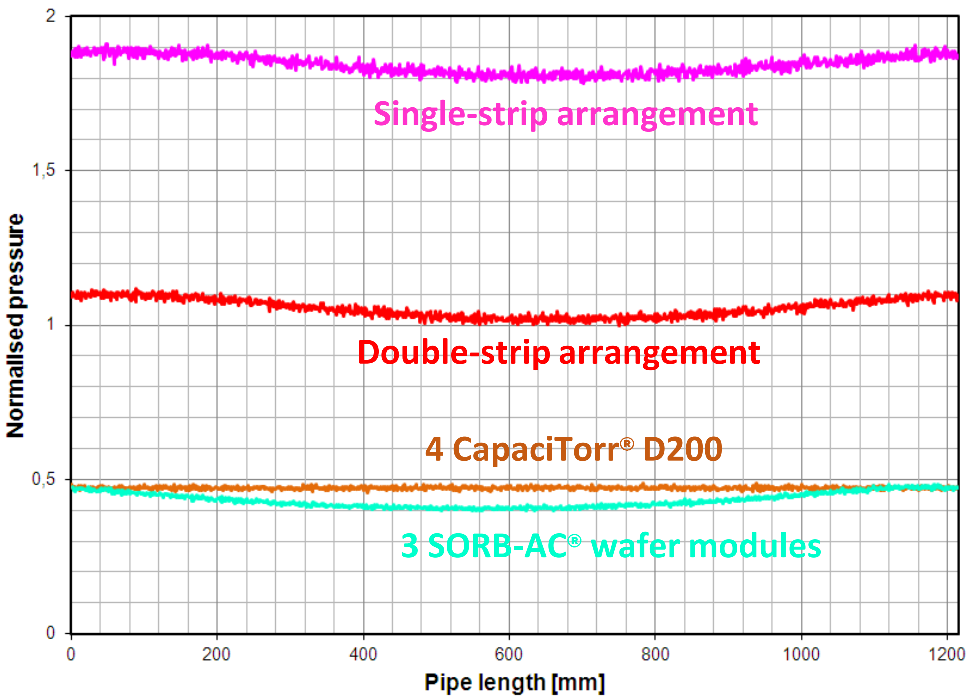


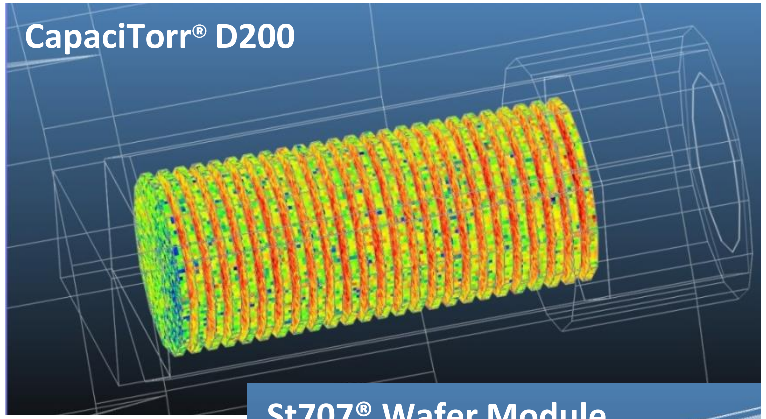


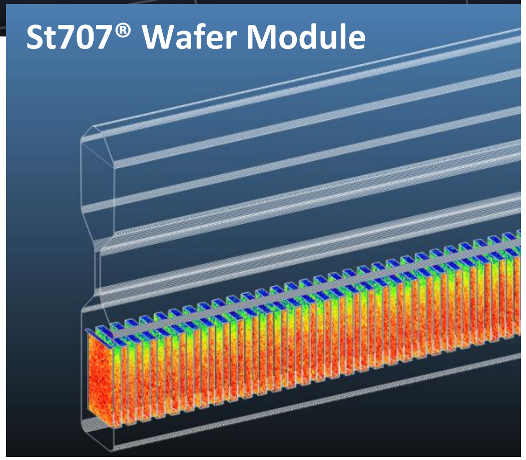
Courtesy of Mr. B. Hippert and Dr. G. Schmidt, DELTA, TU Dortmund

DELTA: distributed vs discrete pumps

- MolFlow+ simulations run for every pumping configuration, in order to make a comparison against the same H_2 outgassing rate
- Getter pumping surfaces were included in the chamber model
- H_2 pressure profile simulated along the beam chamber
- The layout based on discrete pumps is competitive with the distributed-pumping designs



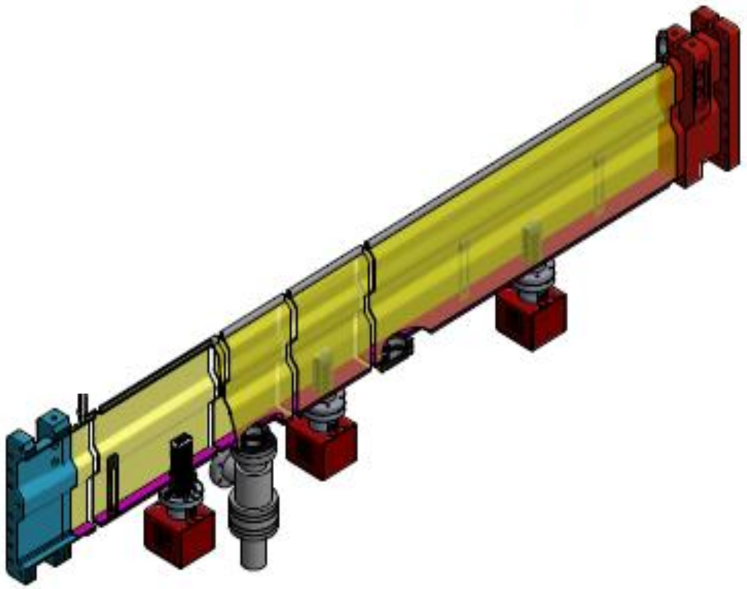


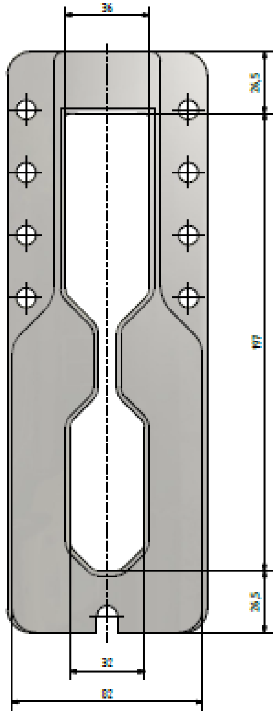


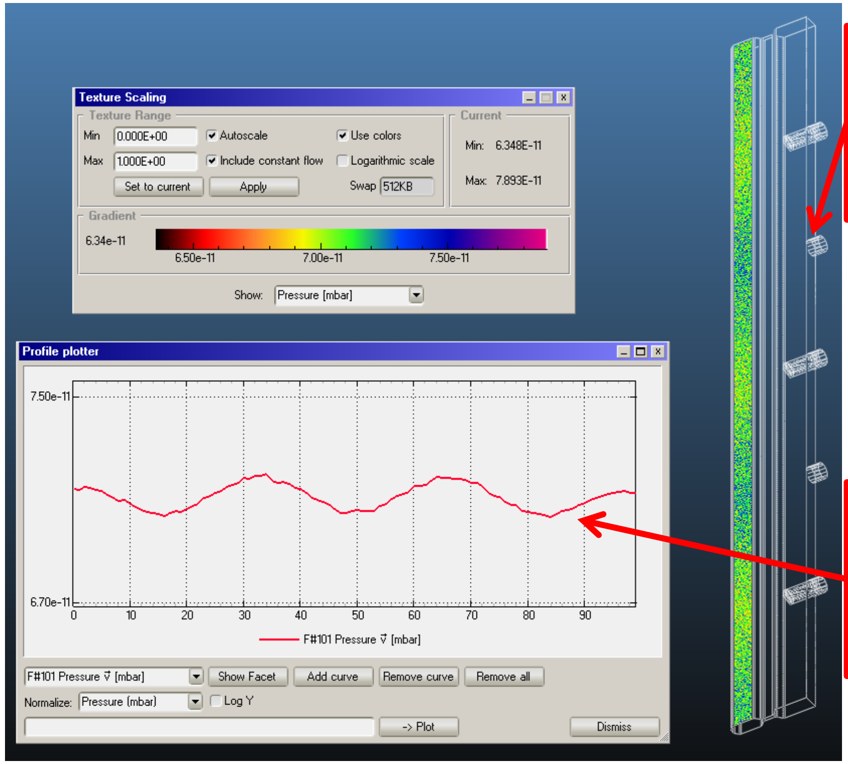
Courtesy of Mr. B. Hippert and Dr. G. Schmidt, DELTA, TU Dortmund

DELTA: modulator chamber

- Total length: ~2 m.
- 3 **NEXTorr® D200-5** installed in CF35 flanges along the modulator chamber and protruding inside the antechamber.







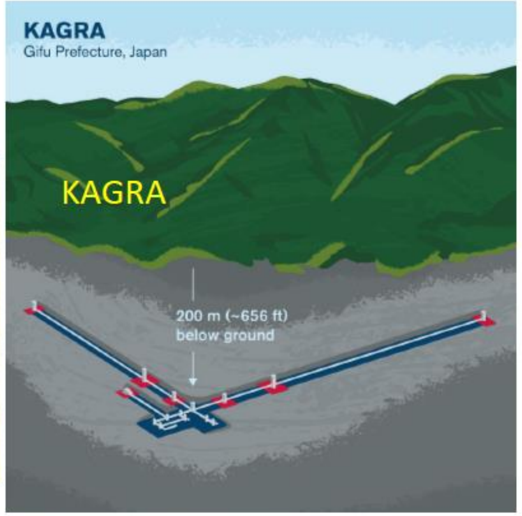
Pressure reading by UHV gauge: **6.8E-11 mbar**

Pressure along the beam channel is quite uniform.

Courtesy of Mr. B. Hippert and Dr. G. Schmidt, DELTA, TU Dortmund

Integration of NEG pumps in gravitational wave detectors (GWDs)

Operating Interferometric
Gravitational Wave Detectors

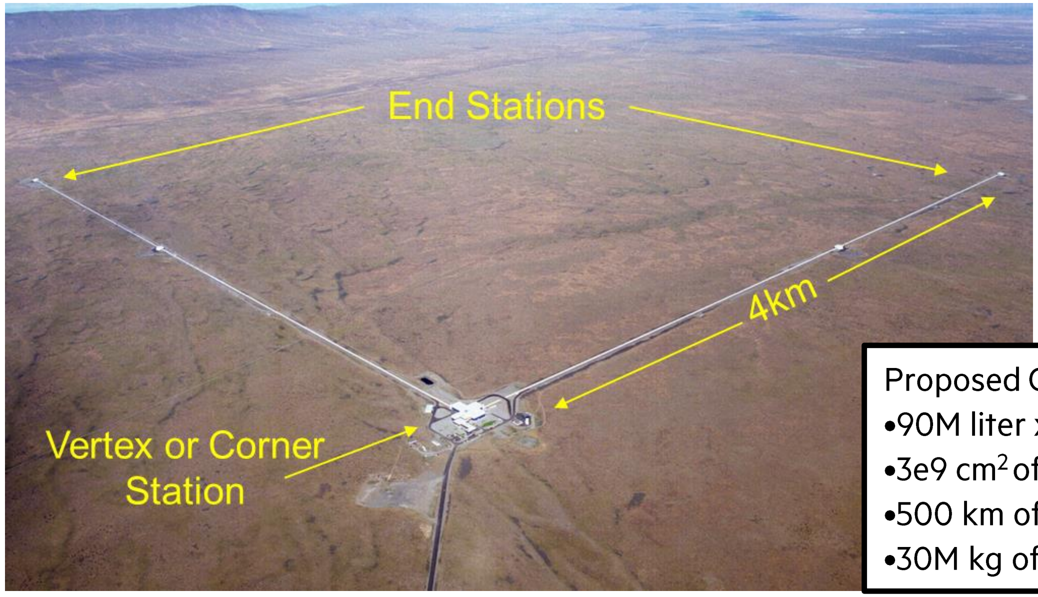


R. Weiss, *Vacuum Challenges for the Next Generation Gravitational Wave Detectors,* Second Vacuum Workshop, CERN, 27 March 2023

Integration of NEG pumps in GWDs: Cosmic Explorer

CE would be a "3rd generation" GW detector:

- Major upgrade vs LIGO, 10x increase arm length 4 km -> 40 km
- 10x increase in strain sensitivity (scales with L). See farther back in time.
- Larger "volume" of observation. Potential 1000x increase in detection frequency.
- Ground based detector similar to LIGO, leverages > 20 yrs. of operational experience.
- Minimal reliance on "new" technologies that may not become available.
- Minimal increase in noise sources, same overall design as LIGO.



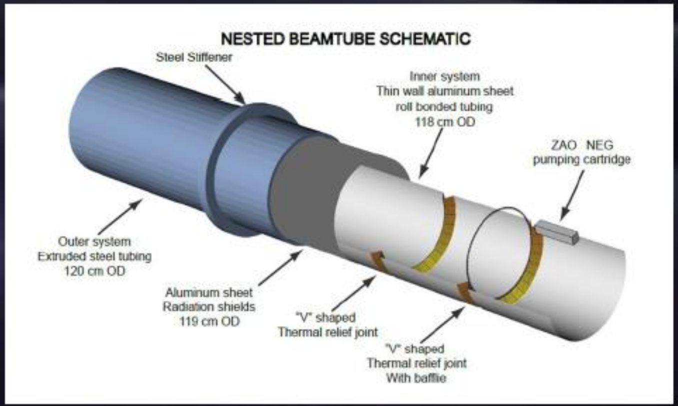
Proposed CE beamtube 80 km
- 90M liter x10^{-9}Torr
- 3e9 cm^2 of surface area
- 500 km of welds
- 30M kg of material (1.27 cm wall)

J. Feicht, LIGO Laboratory, CIT, *CE Beamtube Requirements, Plan and Status, CE Vacuum Workshop*, CERN, March 2023

Integration of NEG pumps in GWDs: Cosmic Explorer

Nested System

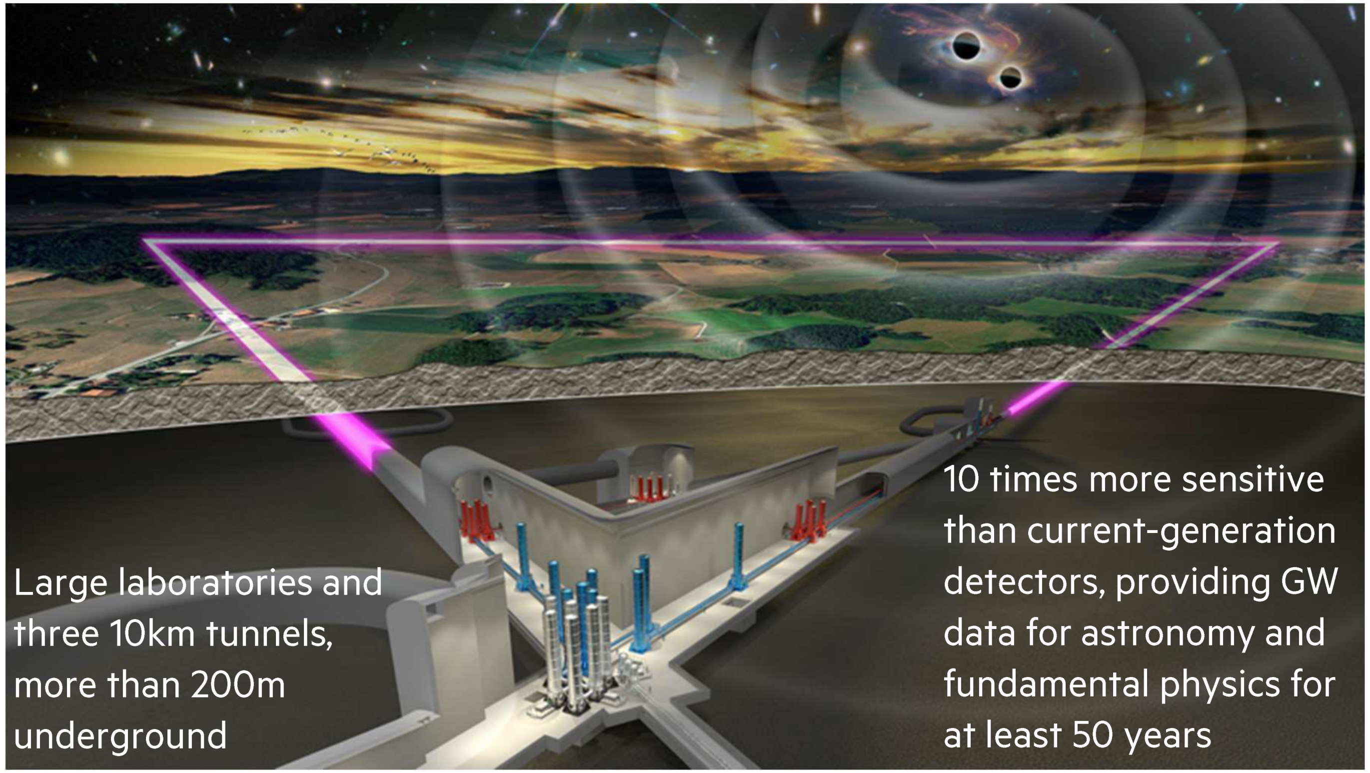
- Complex but has several unique features
  - Steel outer pipe (thickness TBD) with thin (1/2 mm) aluminum inner pipe (could also be thin steel).
  - Modest vacuum (10^{-4} Torr) in annular gap.
  - Thin inner liner resistively heated to bake (same as LIGO).
  - Aluminum is excellent vacuum material. Reflectivity at 1μ?
  - Spiral formed and cold welded (new technology).
  - Gap vacuum: Thermal insulation, crush of inner tube, allows some leaks in inner liner.
  - Complex thermal/electrical isolation, valves need to be developed, unique feedthroughs and ports, manage 2x CTE mismatch between inner and outer systems.
  - Updated design (May 2022) both tubes are steel.
  - ZAO Getter pumps-require feedthroughs to heat. Water speed?
  - Hide ZAO getter behind baffle.

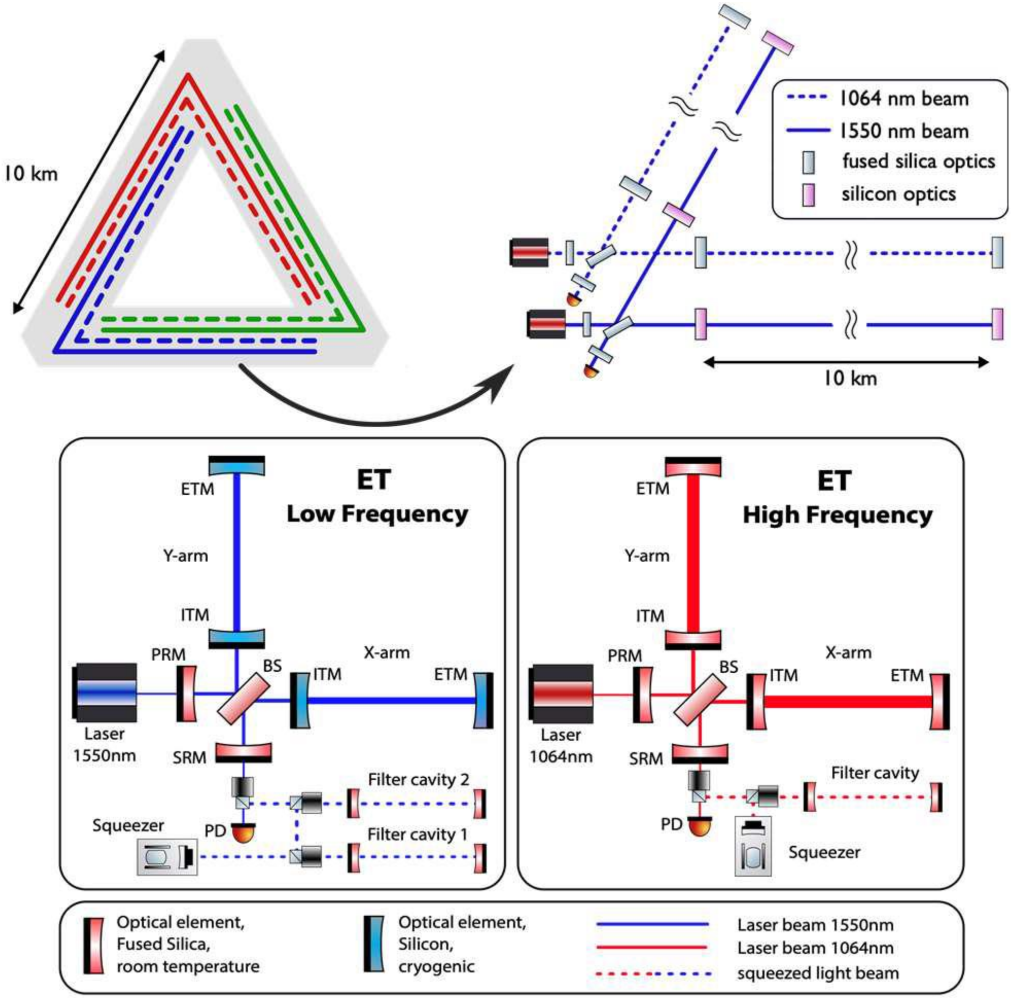


Proposed by R. Weiss

J. Feicht, LIGO Laboratory, CIT, *CE Beamtube Requirements, Plan and Status, CE Vacuum Workshop*, CERN, March 2023

Integration of NEG pumps in GWDs: Einstein Telescope





Rob van der Meer, *Overview of the Einstein Telescope and current status*, Nikhef, NL, 19 December 2023

Integration of NEG pumps in GWDs: Einstein Telescope

HV pumping: NEG pump distribution

Parameters:

D = 1.2 m

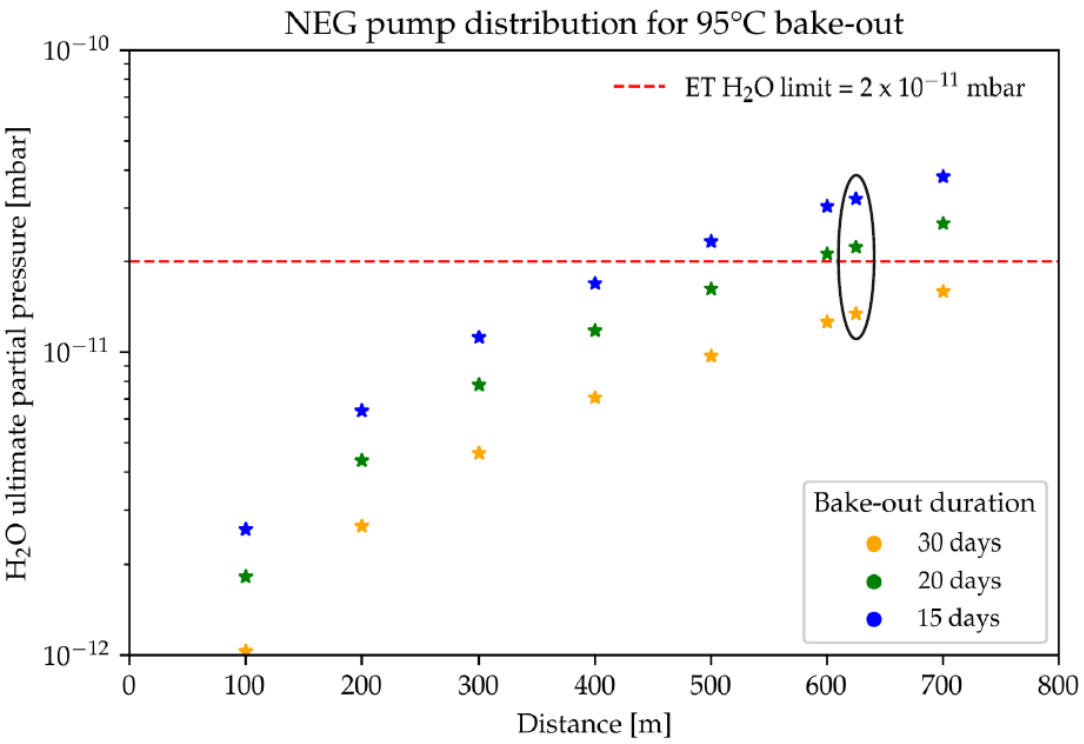
L = 1250 m (distance between two turbos)

TMP pump-down duration: **7 days**

S_{TURBO} = 700 ls^{-1}

S_{NEG} = 1500 ls^{-1} (H_2O)

One NEG pump every 625 m to assist the bake-out cycle

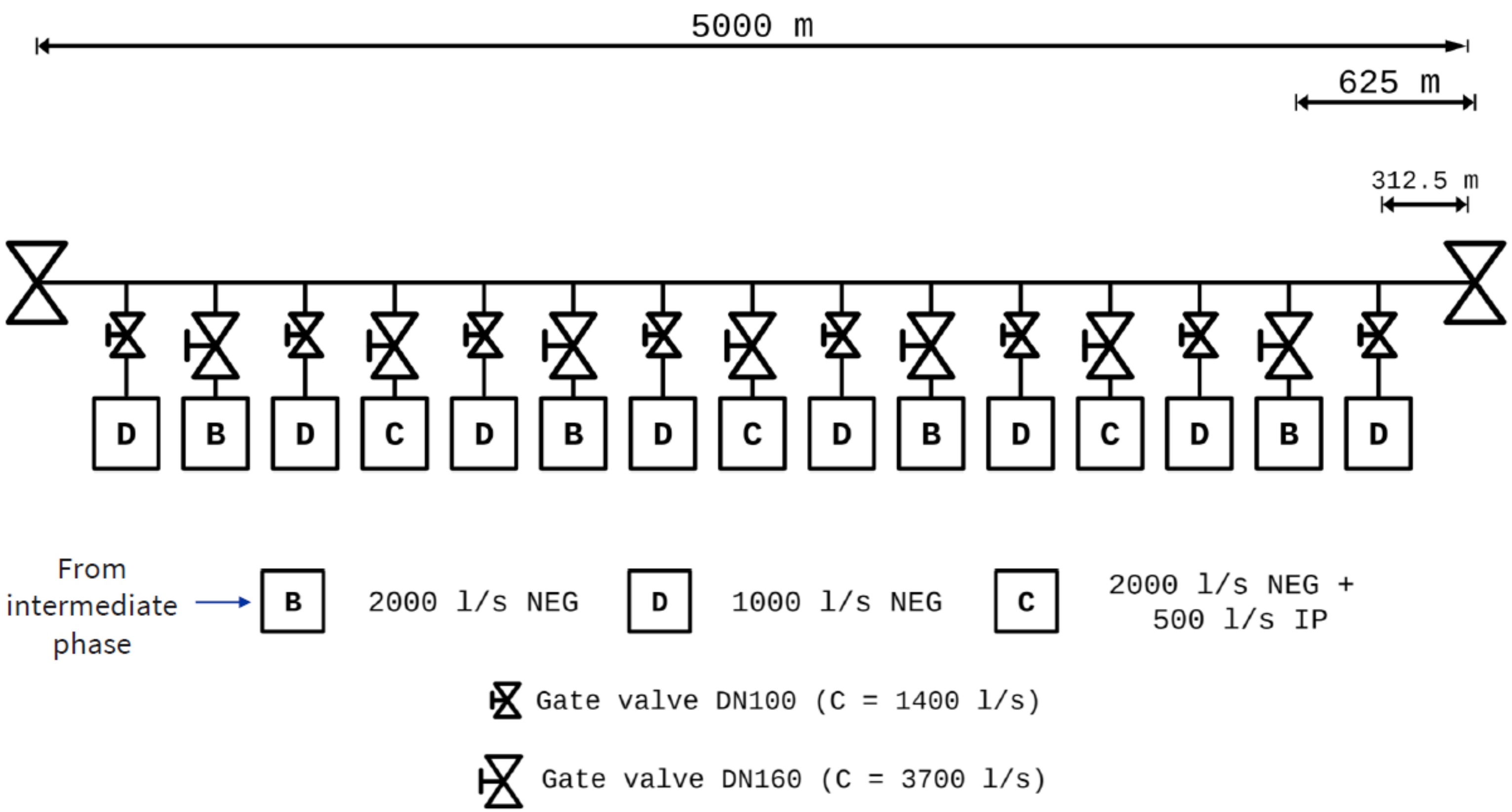


- SAES® HVD has been involved in the design of the pumping system along ET tubes
- First vacuum layout has been conceived for both HV and UHV pumping phases
- The boosted pumping performances given by the presence of the NEG helps in reducing time needed for bakeout

28/03/2022 Carlo Scarcia | Sectorisation, pumping system, commissioning and operation of ET beampipes 21

Integration of NEG pumps in GWDs: Einstein Telescope

UHV pumping at RT: vacuum layout



Carlo Scarcia | Sectorisation, pumping system, commissioning and operation of ET beampipes

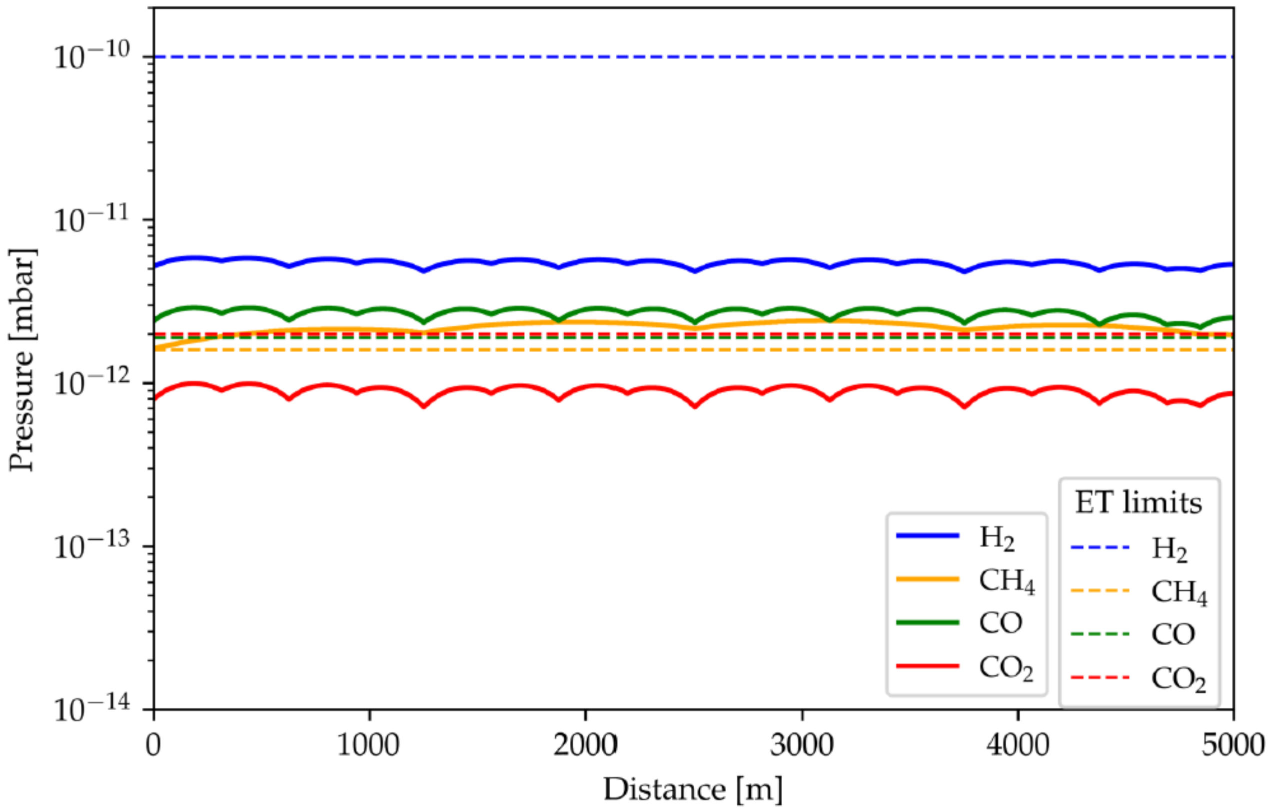
Carlo Scarcia, *Sectorization, pumping system, commissioning and operation of ET beampipes*, CERN, 28 March 2023

Integration of NEG pumps in GWDs: Einstein Telescope

UHV pumping at RT: ultimate pressures

Gas	Pressure from sim. [mbar]	
H_2	6×10^{-12}	✓
CH_4	2.5×10^{-12} *	≈
CO	3×10^{-12} *	≈
CO_2	1×10^{-12} *	✓

- Upper limit (measurement background limited)



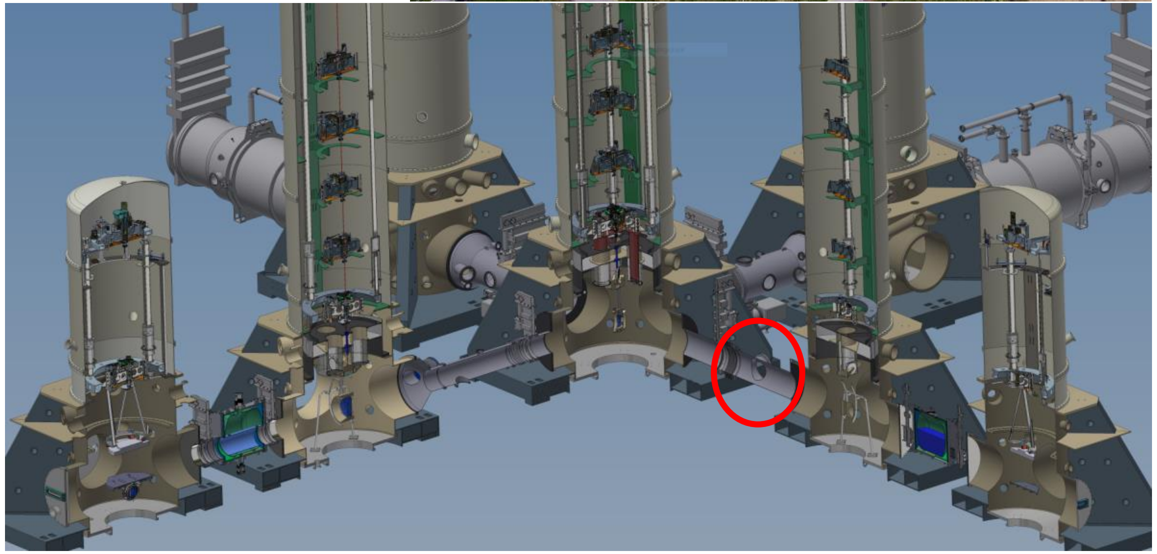
- Distance 0 m = Pressure are going to be much lower due to cryogenics
- Distance 5000 m = DN1250 GV outgassing contribution not considered (a special module is in study to cope with it)
- **Gate valves DN150/DN100 needs extra care, their outgassing rate could be harmful!**

- Preliminary studies on the first conceived pumping system show that a distributed NEG pumping along the tubes meet ET pressure requirements

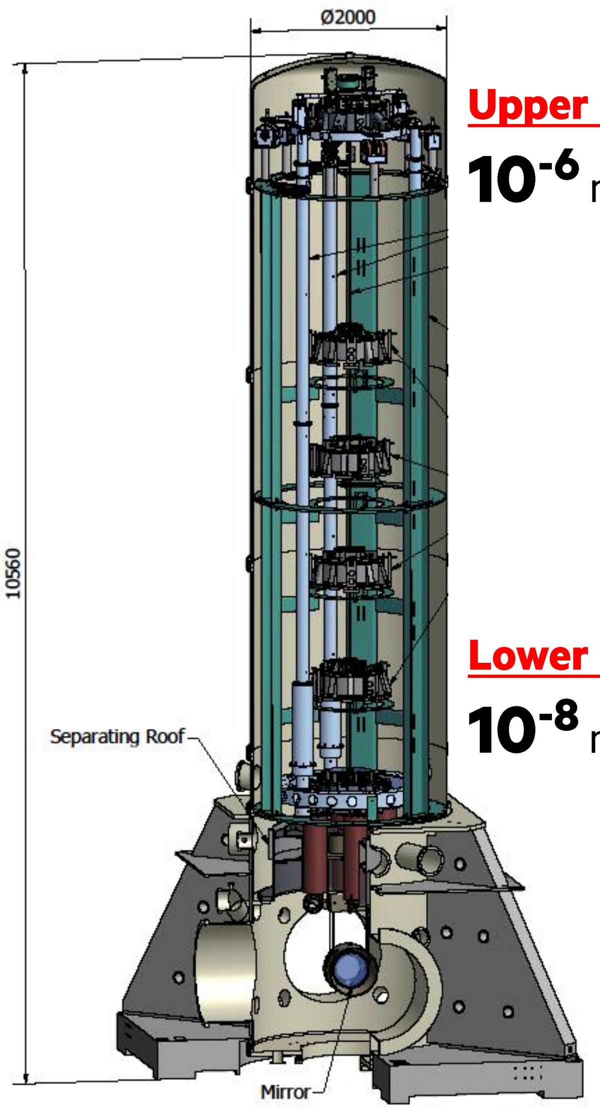
Carlo Scarcia | Sectorisation, pumping system, commissioning and operation of ET beampipes

Integration of NEG pumps in GWDs: VIRGO

- Collaboration for the integration of NEG pumps, exploiting their compactness, pumping performance and absence of vibrations
- Main active gases N_2, O_2
- Reactivation constraints
- Possible customized solutions



Courtesy of VIRGO



Upper Part

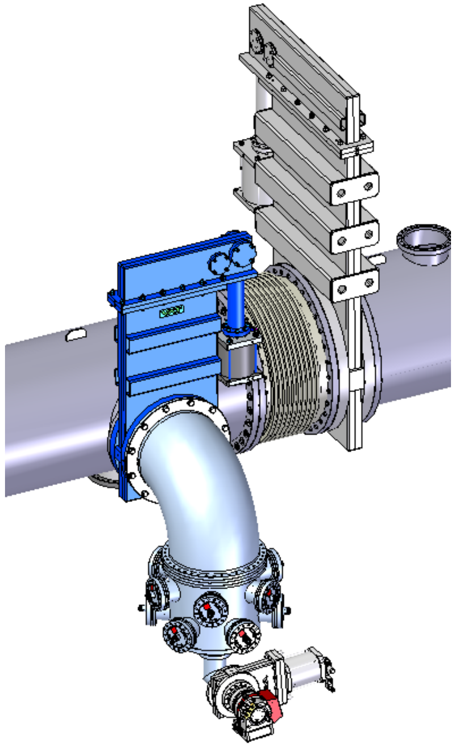
10^{-6} mbar

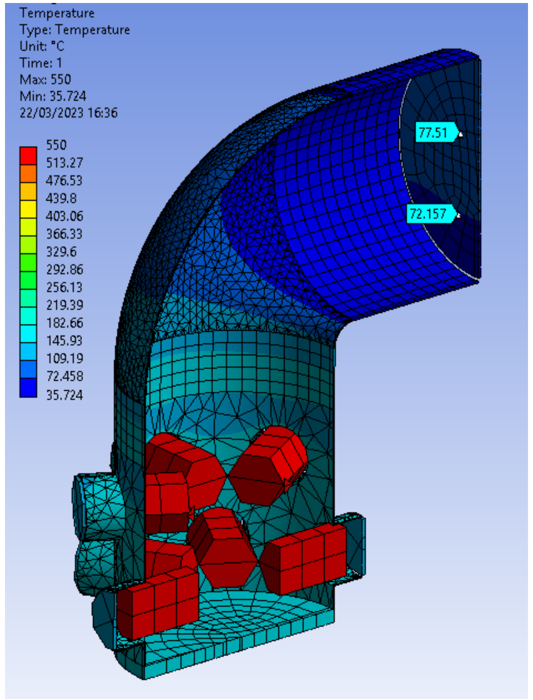
Lower part

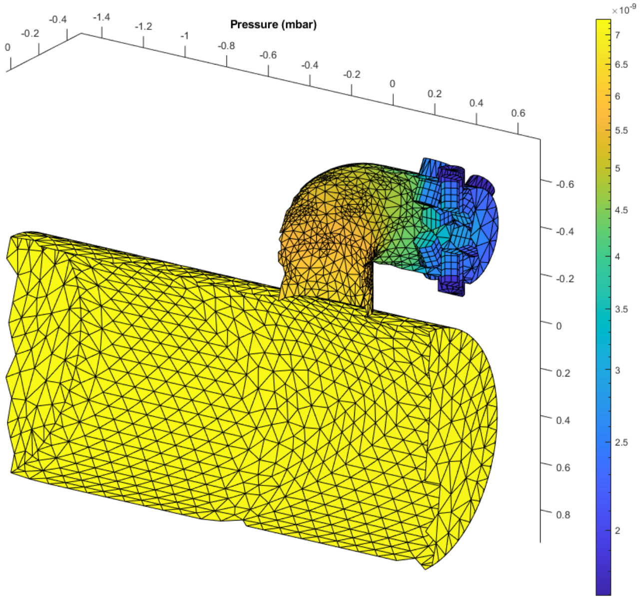
10^{-8} mbar

Integration of NEG pumps in GWDs: VIRGO

- Pumping enhancement module for VIRGO
- CAD project, thermal and vacuum simulation closely linked in iterative process
- Various configurations tested (straight tube, angled elbow, continuous, Tee, etc.)
- Best solution is chosen as the ideal compromise between gate valve, temperature and maximized pumping speed





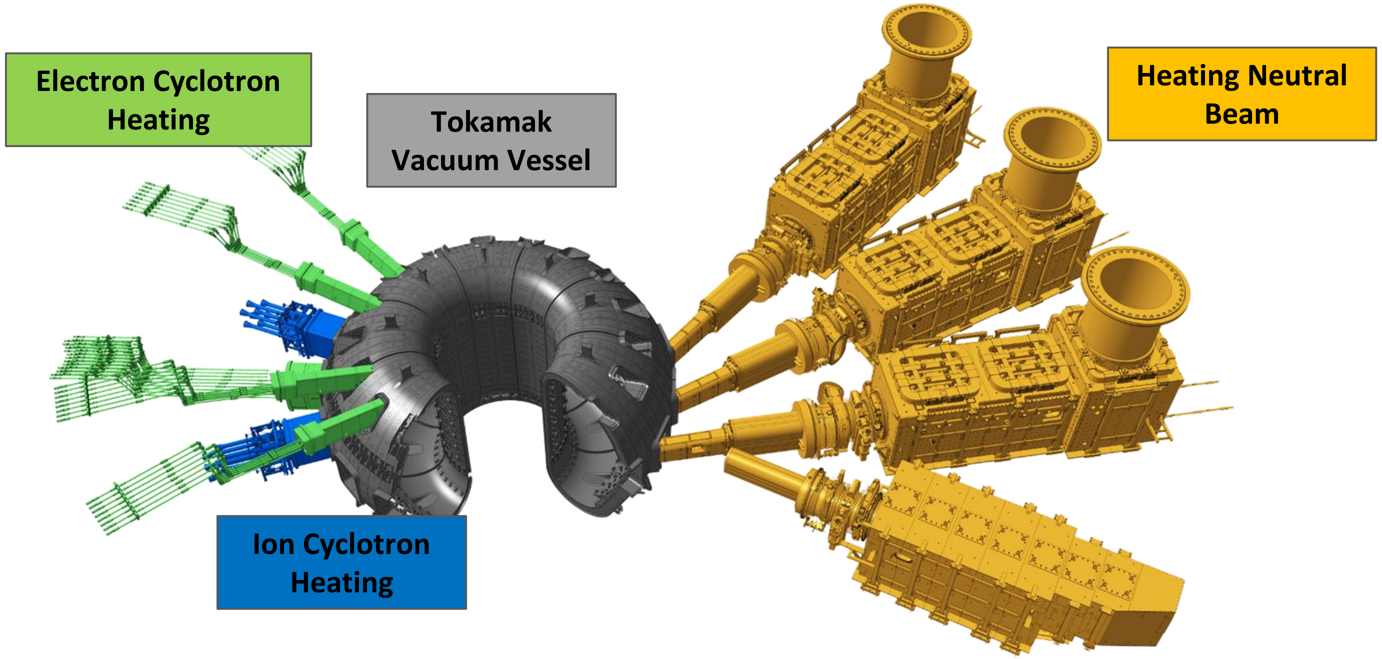


SAES® long history in fusion energy (most recent)

- **2017 Kyushu University – Tokamak QUEST:** CapaciTorr® HV200 used in diagnostic
- **2018 Tsinghua University – SUNIST Tokamak:** CapaciTorr® HV 2100 used in the divertor
- **2018 IPP:** HV 800 wafer module is under test in the divertor
- ***2018 – LHD at NIFS***: installation 42 NEG HV 400 wafer modules in the divertor
- ***2018 ITER:*** NEXTorr® HV 200 in the transfer line of ECRH
- ***2014 → DEMO NBI[(1)-(4)]***
- ***2021 → Mega NEG pump for SPIDER***

1. M. Siragusa et al, Conceptual design of scalable vacuum pump to validate sintered getter technology for future NBI application, Fusion Engineering and Design, 146, 87 (2019)
2. F. Siviero et al, Characterization of ZAO® sintered getter material for use in fusion applications, 146, 1729 (2019)
3. Siviero F. et al, Robustness of ZAO® based NEG pump solutions for fusion applications, 166, 112306 (2021)
4. E. Sartori, Design of a large nonevaporable getter pump for the full size ITER beam source prototype, JVSTB, 41, 034202 (2023)
5. M. Baquero-Ruiz et al, Non-evaporable getter pump operations in the TCV tokamak, 165, 112267 (2021)
6. Alternative solution for the MITICA/HNB vacuum pumps jointly developed by SAES® and RFX, private document (2013)

Neutral Beam Injectors



- Essential plasma-heating device in fusion facilities, both existing (JET, ASDEX, JT-60SA, W7-X, LHD etc.) and under construction/design (ITER, DTT, DEMO…)
- Produces a highly energetic and *neutral* H_2/D_2 beam
- Example ITER NBIs : 1MV acceleration, 16 MW power D_2 beam

- In 2014-2021 SAES® has been involved to develop a NEG pump for the Neutral Beam Injector (NBI) of DEMO
- The NEG technology validation has been accomplished and the results have been published in more papers and accepted from the fusion community

- DEMO pre-conceptual design – Tritium Fuelling Vacuum (TFV) WorkPackage
- activity 3.6 "Development of a NEG-based pumping concept for NBI pumping "

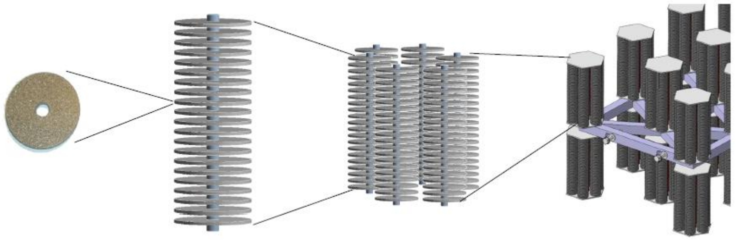
CONSORZIO RFX Ricerca Formazione Innovazione

saes

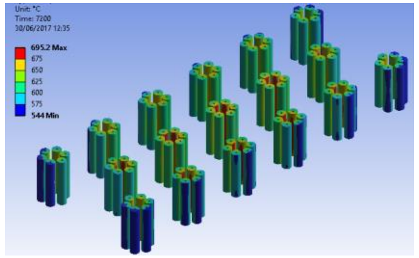
KIT Karlsruhe Institute of Technology

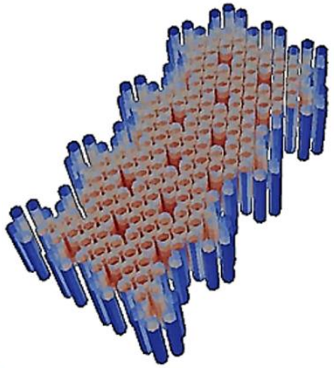
The way to a NBI-scale NEG pumping system

From ZAO® disk to multi-stack cartridge

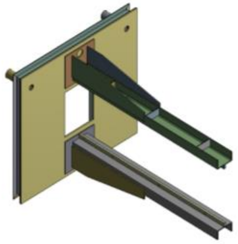


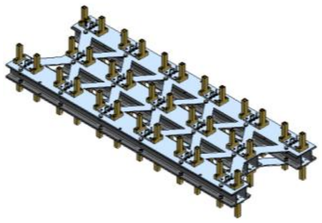
Vacuum and thermal simulations





Design and construction



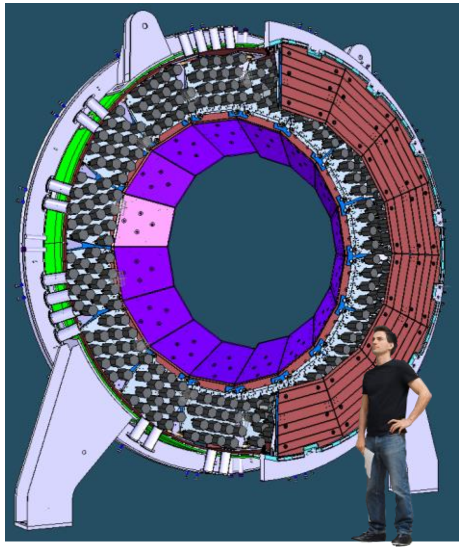


Assembling and characterization

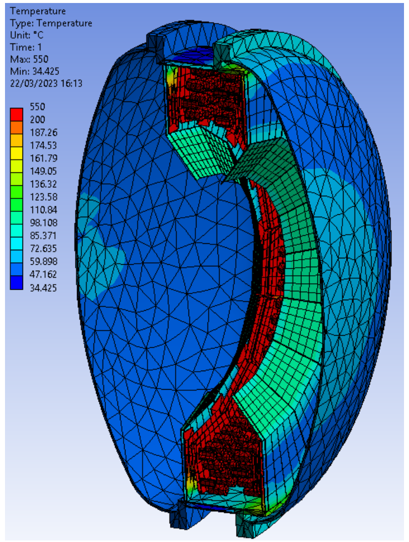
40.000 l/s (H2) pump tested at TIMO facility at KIT

F. Siviero et al., *Testing of a large Non-Evaporable Getter pump mock-up in view of application in modern Neutral Beam Injectors, AIV XXV, 2023*

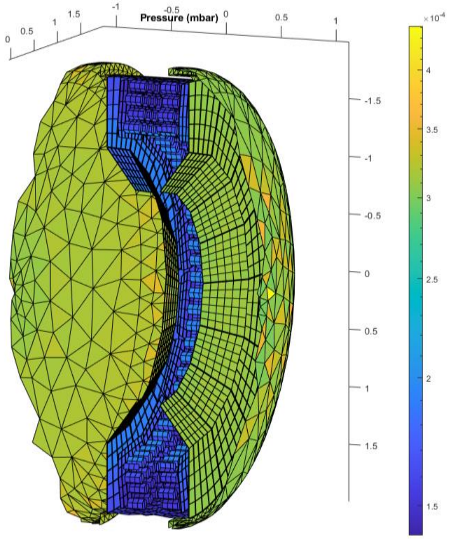
Coming next: SPIDER Vacuum system upgrade (Consorzio RFX, Padova)



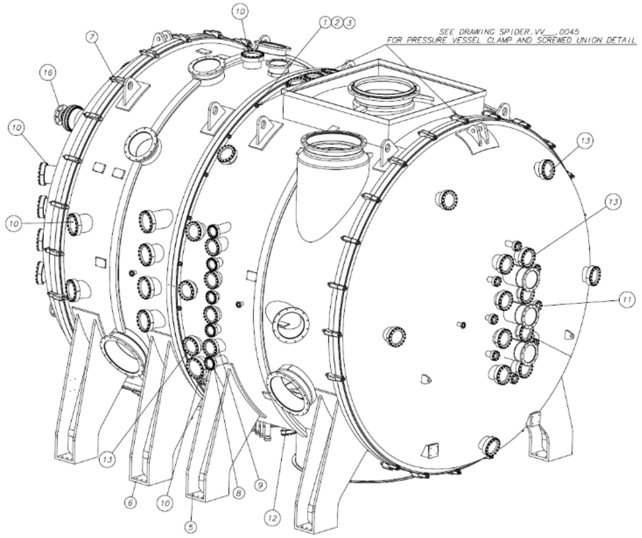
CAD model

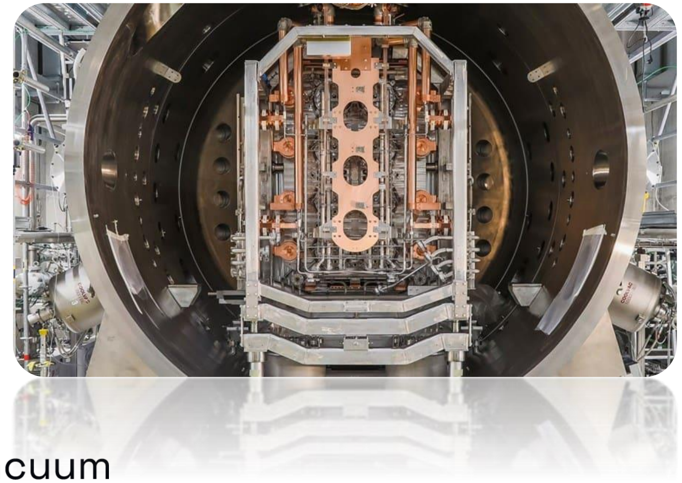


Thermal analysis



Vacuum analysis



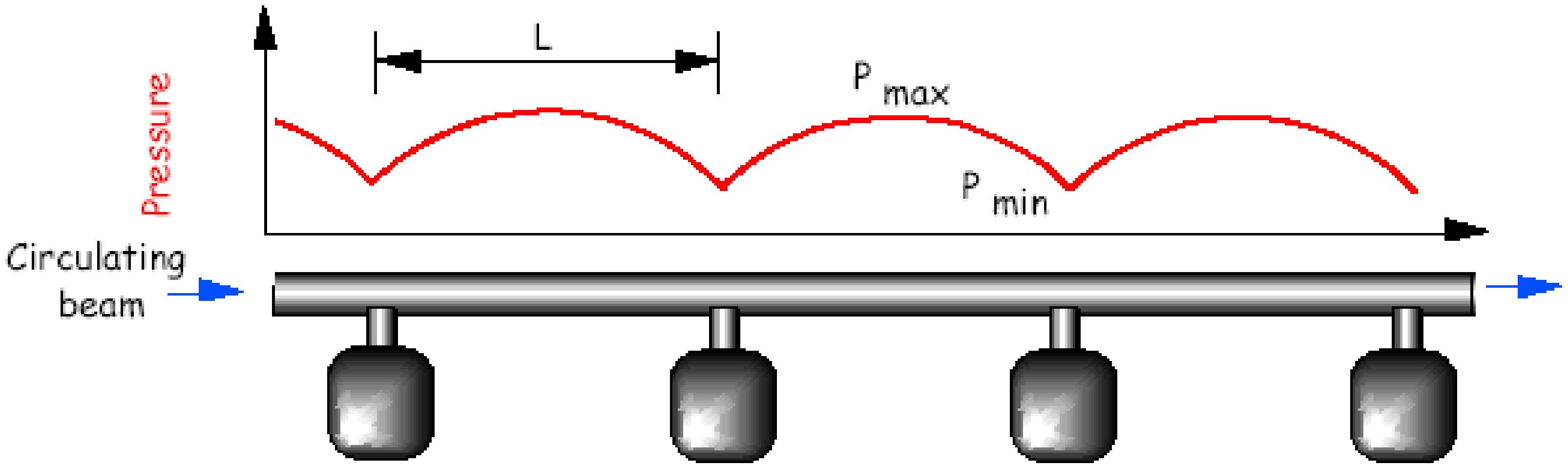


- The testing facility of the NBI of ITER is under test at Consorzio RFX (MITICA)
- In the source of the NBI (SPIDER), RFX is integrating a ZAO® NEG pump of 340.000 l/s (H_2) @10^{-4} mbar
- This solution integrates 384 NEG cartridges (upgradable to 512): largest NEG pumping system in the world
- Thermally shielded pumping system: thermal and vacuum studies closely linked
- Power supply, electronics and SW integrated within the overall experiment control system

DISTRIBUTED PUMPING: NEG COATING

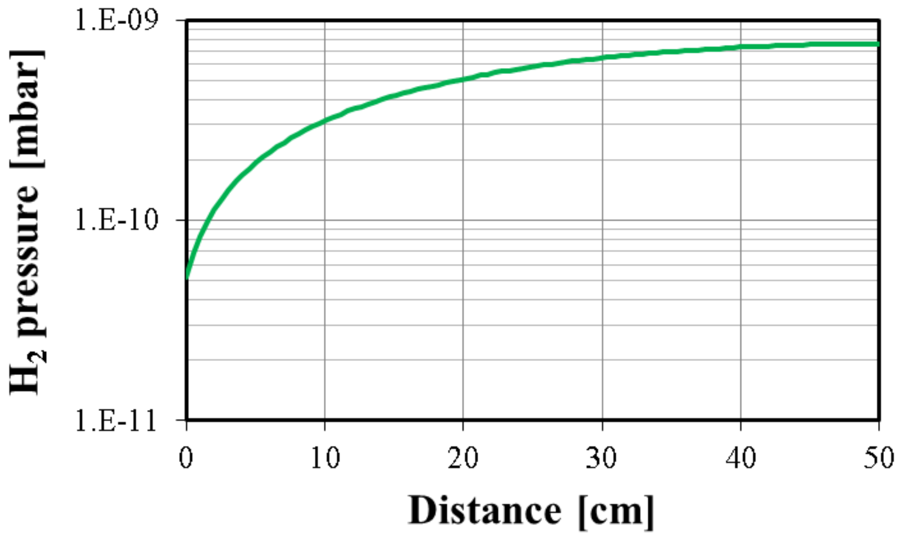
TRADITIONAL PUMPING APPROACH FOR STORAGE RINGS

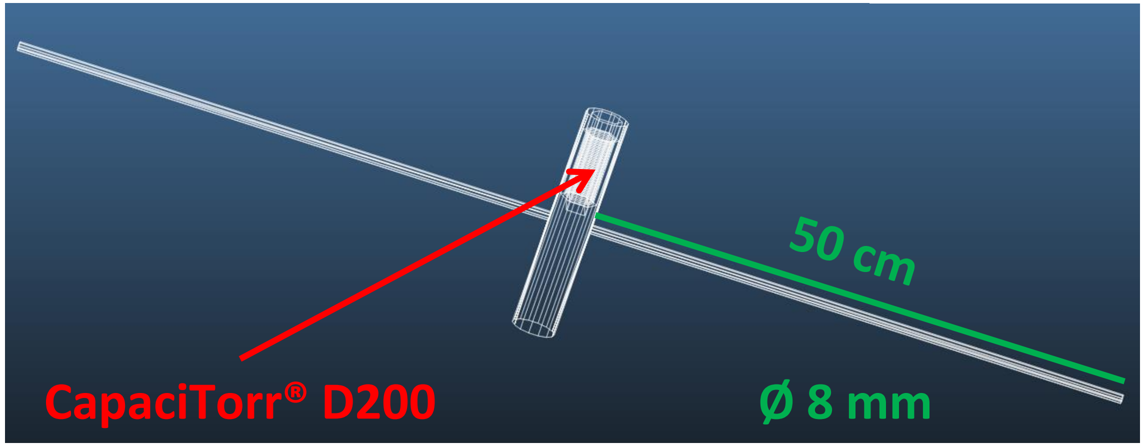
- The required beam-on pressure for machine operation in a storage ring should be at least in the **10^{-9} mbar range** or lower, in order to guarantee the design beam lifetime, which is typically of several hours.
- To meet the required **ultra-high vacuum** (UHV) conditions, the traditional approach is based on a distribution along the ring of **discrete pumps** (SIP, NEG, TSP) installed on appropriate side flanges.
- The resulting pressure profile along the beamline is **parabolic**.



PUMPING SOLUTIONS FOR NARROW-GAP BEAM PIPES

- When dealing with small-aperture beam pipes and narrow-gap IDs, discrete pumps in principle are not the best solution.
- Pumping speed is severely affected by the strong conductance limitations given by the geometry.
- Big pumps cannot be used due to the space constraints given by the compact magnet lattice.





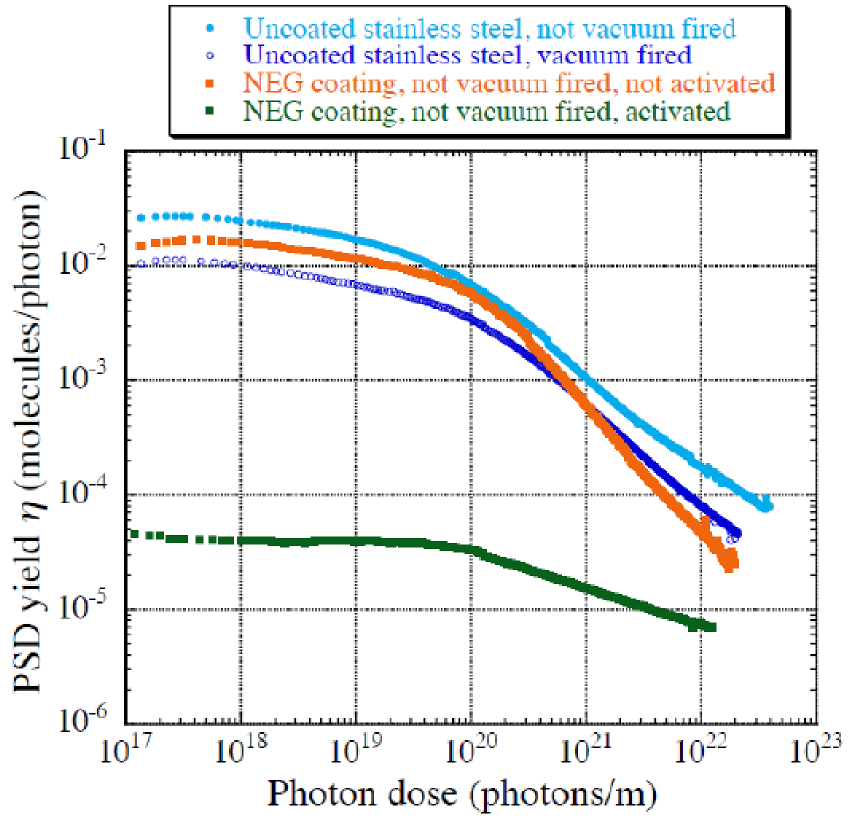
Distributed pumping is the most suitable solution for conductance-limited systems.

NEG COATING FOR NARROW-GAP BEAM PIPES

NEG coating becomes the best way to provide distributed pumping and to ensure the required UHV level and beam lifetime.

NEG coating:

- Provides a distributed pumping solution
- Mitigates the effect of small conductance on pumping speed
- Transforms the pipe wall, from a source of gas to a pumping surface
- Has a low SEY, mitigates PSD and ESD
- Can effectively pump most gases (H_2, H_2O, CO, N_2, O_2, CO_2), except for noble gases and hydrocarbons



NEG COATING: main features

- NEG coating: as a vacuum pump for particle accelerators was developed and patented at CERN and widely used in the LHC (Large Hadron Collider)
- Typical NEG coatings are ~1 µm TiZrV, deposited by magnetron sputtering
- NEG coating can be activated at low temperature (e.g., 180 °C x 24 hours) during machine bake-out
- Several machines worldwide have already implemented this technology to boost machine performance & design

$$S = \frac{1}{4} \cdot \langle v \rangle \cdot \alpha \cdot A$$

STICKING FACTOR α

[1]

NEG surface	α H_2	α CO	α N_2
Smooth	$8 \cdot 10^{-3}$	0.7	$1.5 \cdot 10^{-2}$
Rough	$3 \cdot 10^{-2}$	0.9	$3 \cdot 10^{-2}$

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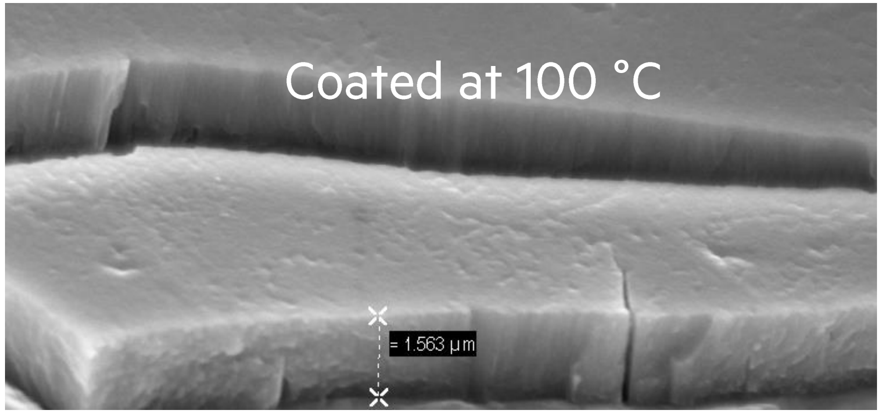
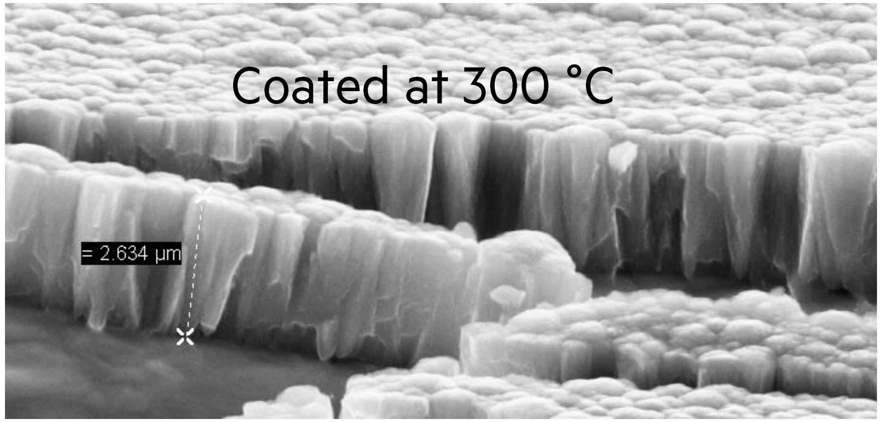
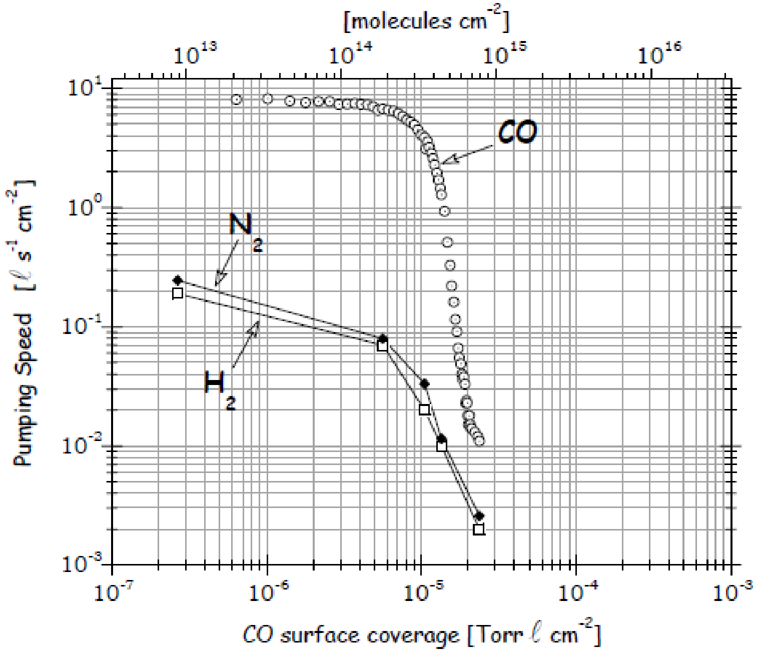
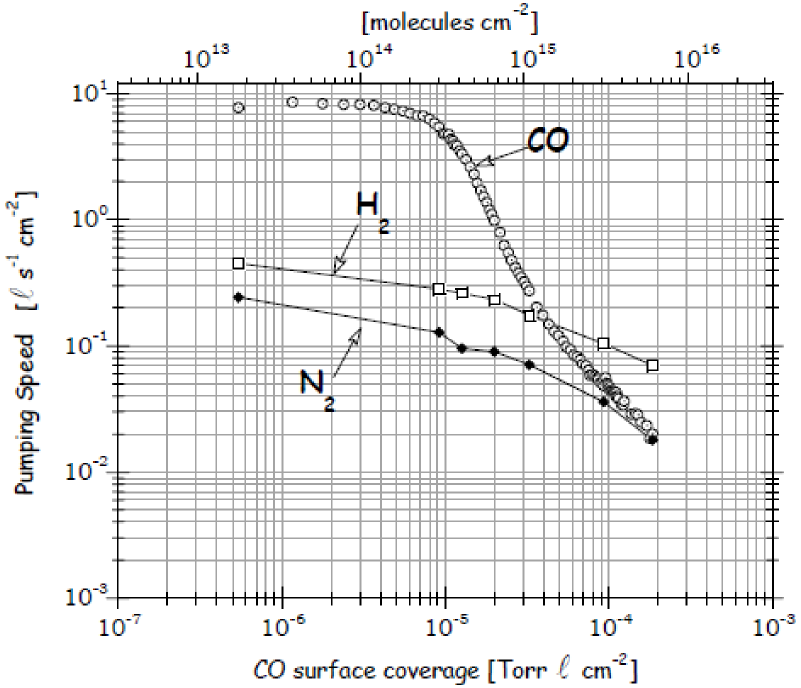
[1] P. Chiggiato, P. Costa Pinto, Thin Solid Films 515 (2006)

NEG COATING: pumping properties









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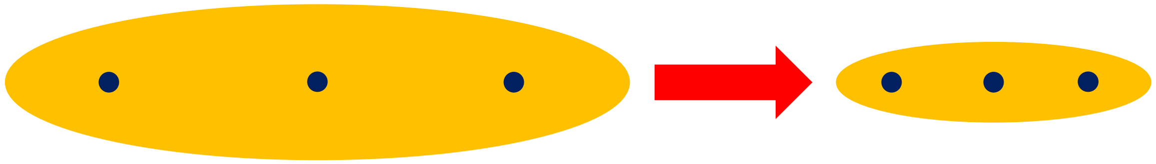
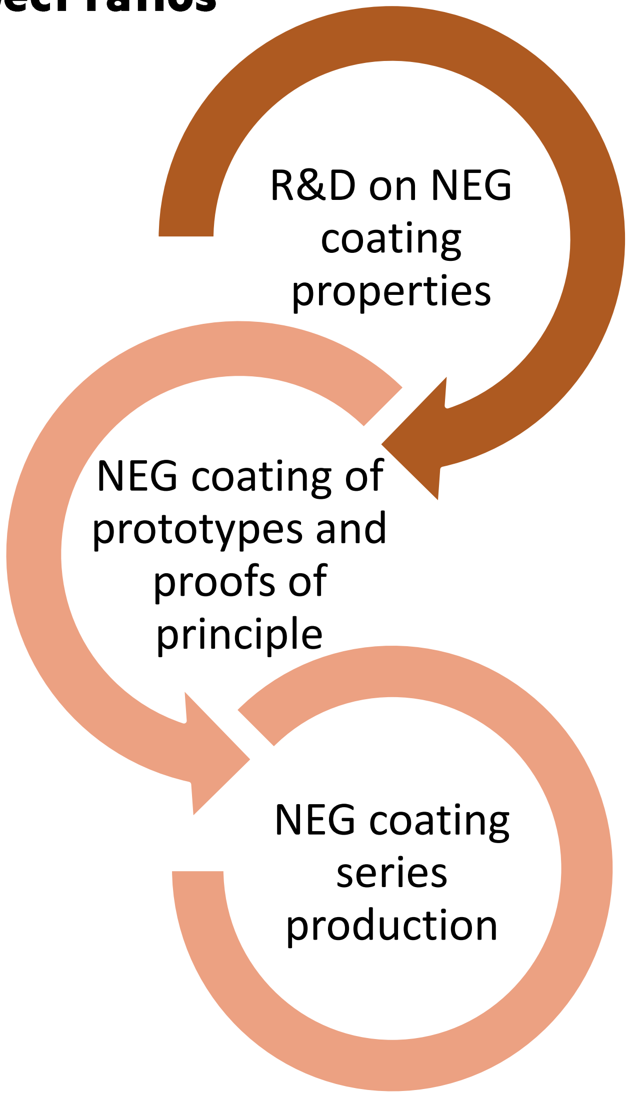
P. Chiggiato, P. Costa Pinto, Thin Solid Films 515 (2006)

NEG COATING critical issues of complex shapes and high aspect ratios

- **Inserting** and **positioning** the cathodes
- **Plasma volume** is very limited

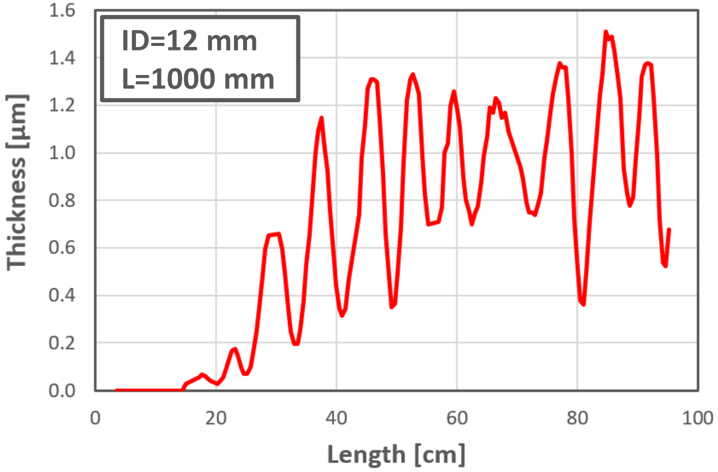


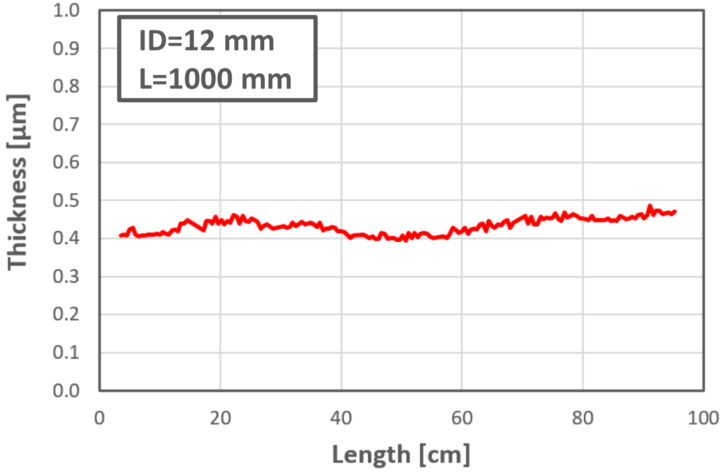
- Risk of cathode **misalignment**
- **Cleaning** is not straightforward
- **Controlled NEG thickness** in electron beam pipes
- Presence of **delicate components** (BPMs, bellows, beam screens, RF fingers, …)
- **Pumping characterization** is very challenging



NEG COATING properties and fine tuning

µ-XRF analyses





SAES proprietary process --> NEG film thickness control

- **Low impedance** is a key requirement of new synchrotron light sources
- A **thin** and **uniform** NEG film is need to meet such requirement
- It is necessary to fine tune the sputtering process
- When coating chambers with complex shapes and high aspect ratios, this is **not straightforward**

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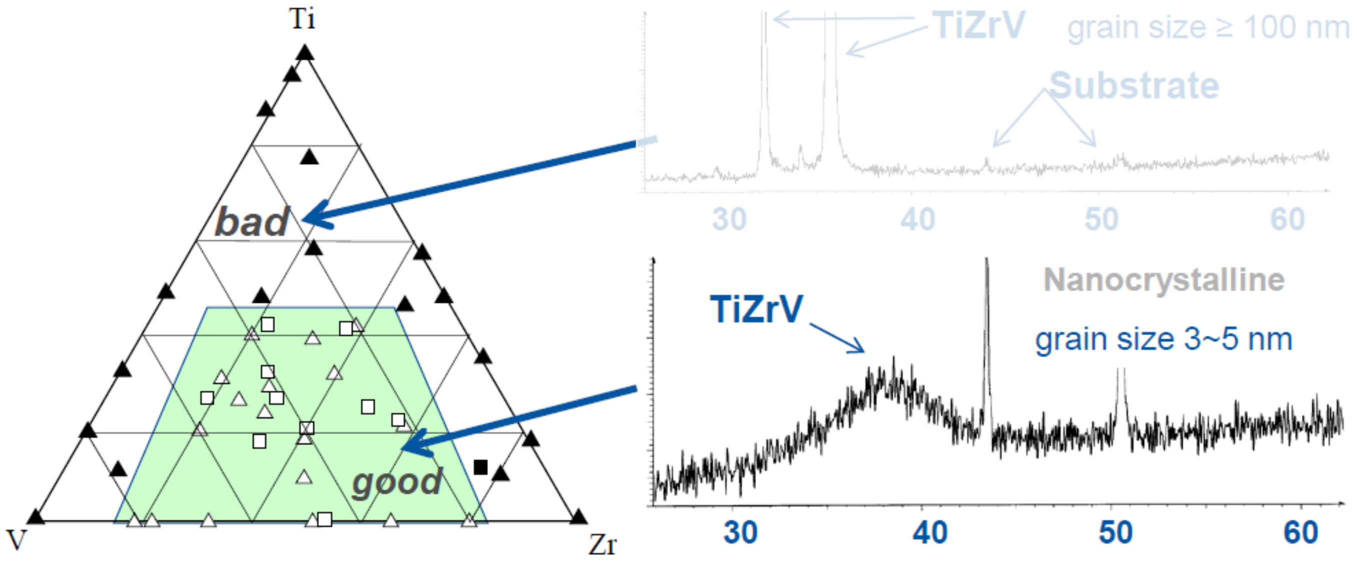
NEG COATING properties and fine tuning

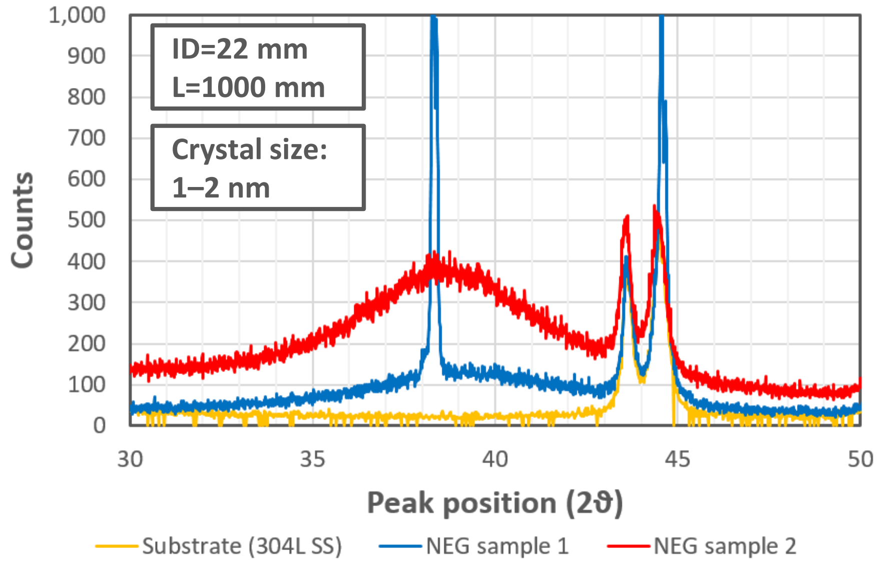
P. Costa Pinto, 80th IUVSTA Workshop, 2016, Taiwan



- Activation temperature should be low enough to be compatible with UHV materials and components (e.g., aluminium)
- The low activation temperature of TiZrV coating is influenced by the crystalline structure of the film [1]
- Grains of nanometric size (3–5 nm) --> oxygen transport increase through grain boundaries --> low activation temperature
- XRD analysis can be used to monitor the crystalline structure of deposited films

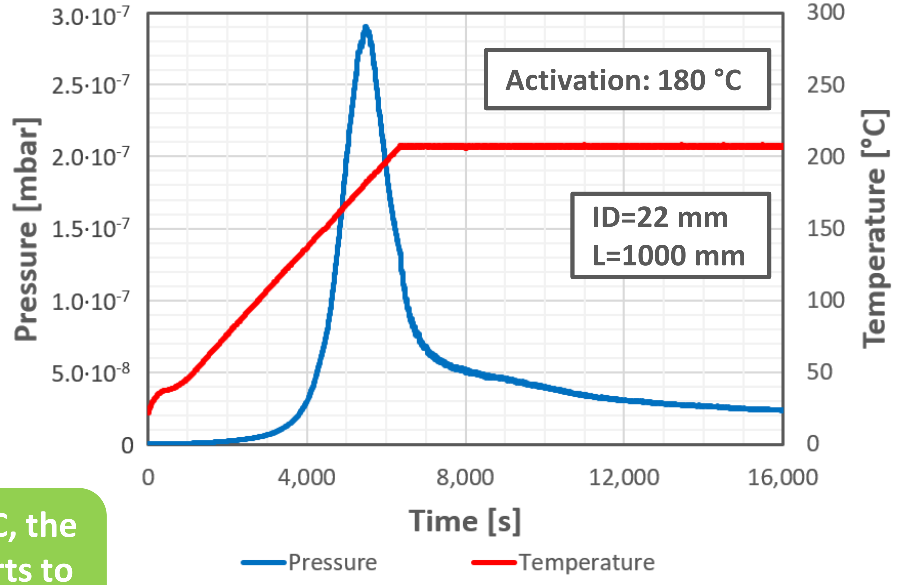
[1] P. Chiggiato, P. Costa Pinto, Thin Solid Films 515 (2006)

NEG COATING properties and fine tuning



XRD analysis of a NEG film

At 180 °C, the NEG starts to pump



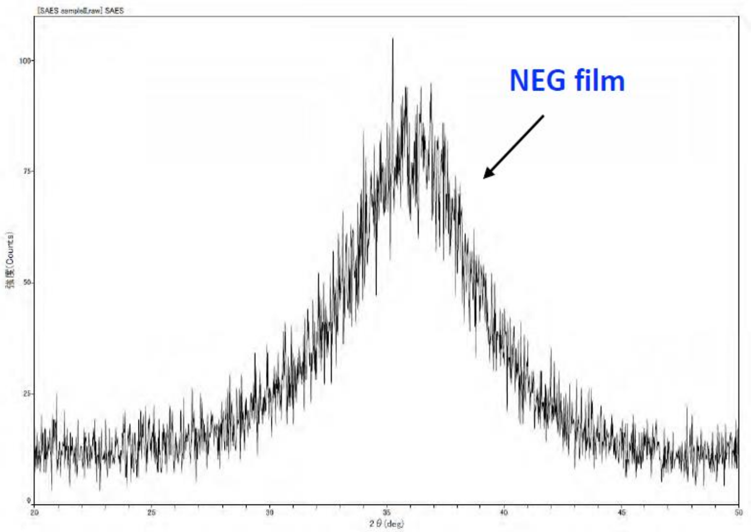
Pressure profile during NEG activation

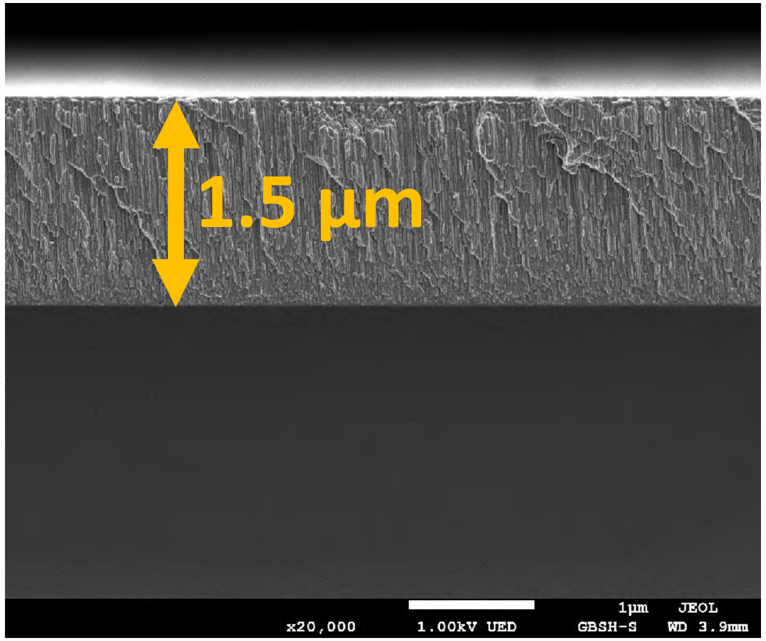
- Activation temperature should be low enough to be compatible with UHV materials and components (e.g., aluminium)
- The low activation temperature of TiZrV coating is influenced by the crystalline structure of the film [1]
- Grains of nanometric size (3–5 nm) --> oxygen transport increase through grain boundaries --> low activation temperature
- XRD analysis can be used to monitor the crystalline structure of deposited films

[1] P. Chiggiato, P. Costa Pinto, Thin Solid Films 515 (2006)

PF-ring Undulator #19 (KEK, Japan)

- 90x15 mm elliptical cross-section
- Chamber length: 4100 mm
- NEG film thickness is well controlled and in accordance with calculations
- NEG activation: 48 h at 160 °C [1]



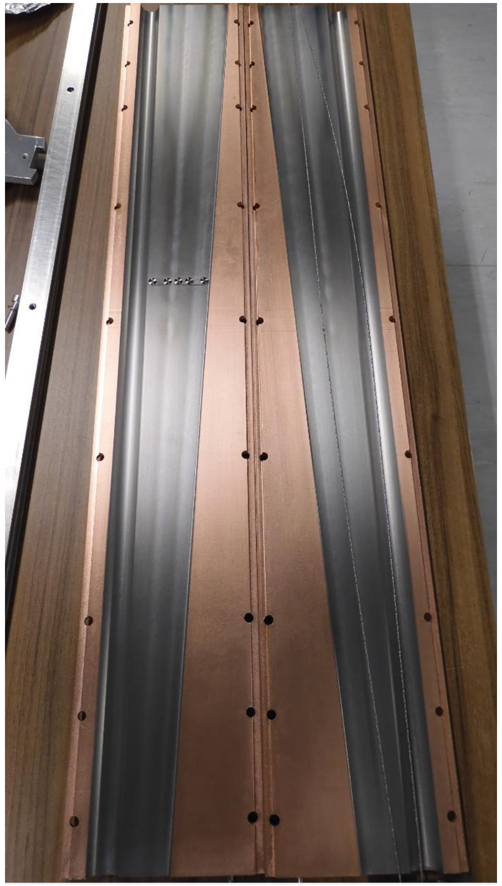


Crystallite size: **1.6 nm** (from Scherrer equation)
--> Good NEG activation at 160 °C [2]

[1] Y. Tanimoto, Proceeding IPAC19
[2] P. Chiggiato, P. Costa Pinto, Thin Solid Films 515 (2006)

ALS-U storage ring VC03 (LBNL, USA)

- Many critical aspects:
    - 5 mm gap keyhole
    - Variable horizontal section
    - Need for several cathodes
    - Plasma ignition everywhere
    - Spacing between cathodes is very important to achieve a uniform deposited thickness
- NEG coating fine tuning on a two-shells prototype
- NEG coating of the complete vacuum chamber



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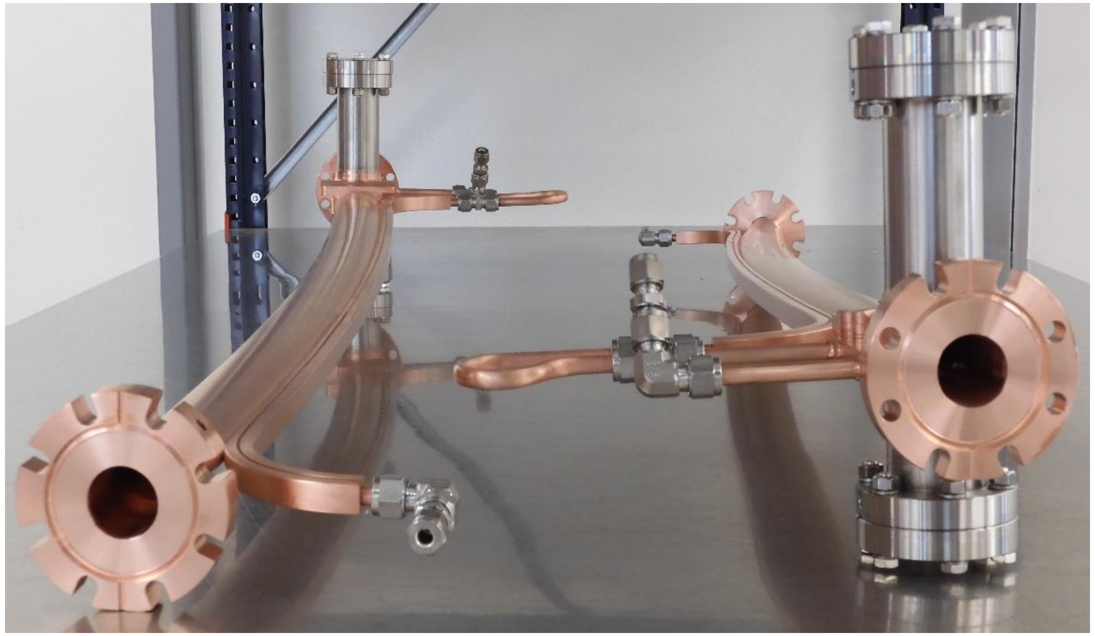
Courtesy of Sol Omolayo, LBNL

ALS-U Accumulator-Ring dipoles (LBNL, USA)

- Many critical aspects:
    - Strong curvature
    - Section transitions (circular-elliptical-circular)
    - No direct visual through the end
    - Need for special cathode holders
- 1st article coated in 2022
- Series of 30 chambers coated in 2023

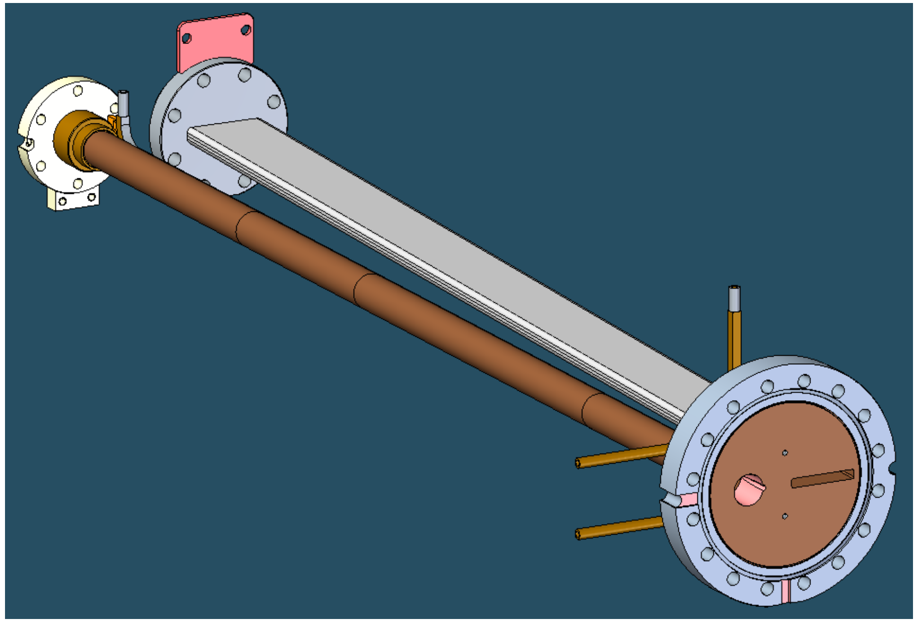


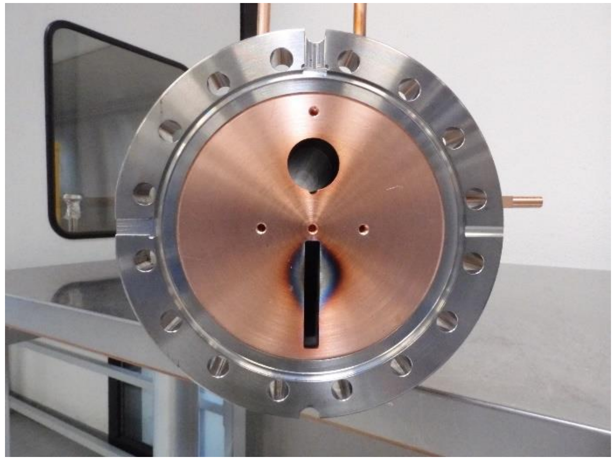
Courtesy of Sol Omolayo, LBNL

LM Girder Vessel 3 (DIAMOND, UK)

Two separate channels diverging from the same flange:

- DN20 circular electron beam pipe (OFS Cu)
- 45x6 mm rectangular photon beam pipe (SS 316L)





Courtesy of Toby Lockwood, Diamond Light Source

Appendix
SAES®, SRV, Cinel: integrated solutions for vacuum applications

SAES RIAL Vacuum

- Established in December 2015 in Parma with the aim to design manufacture, test and supply vacuum systems to the industry and research.
- Since May 2022 is 100% part of the SAES® Group
- Strong increase of sales thanks to the acquisition of large contracts for accelerators (APS, LBLN, ESRF, CERN...)

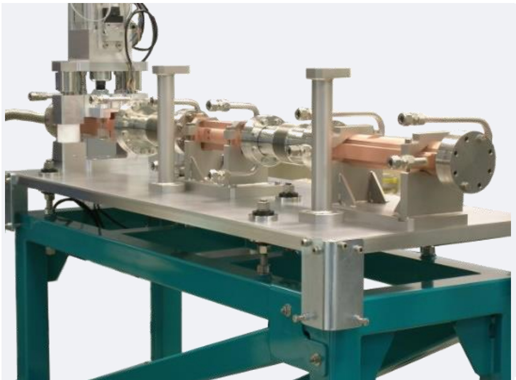
Technology for the accelerator community

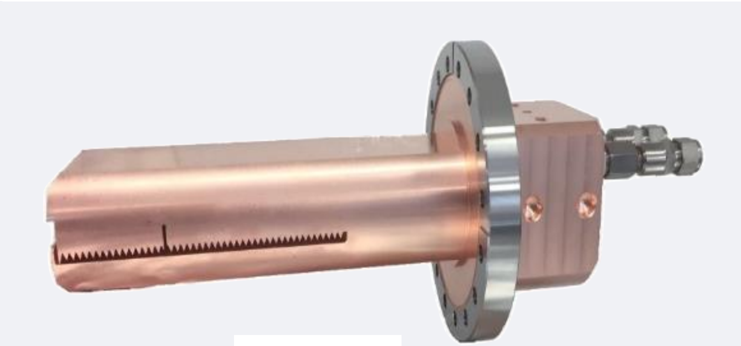
- SAES RIAL Vacuum serves both the light sources and colliders communities..
- Typical products/solution for synchrotrons are
  - Chamber for in vacuum & in air-undulator
  - Chambers for the storage rings and special chambers
  - Crotch absorbers, BPM, taper, RF bellows
  - Bunch compressors…

In vacuum undulator chambers

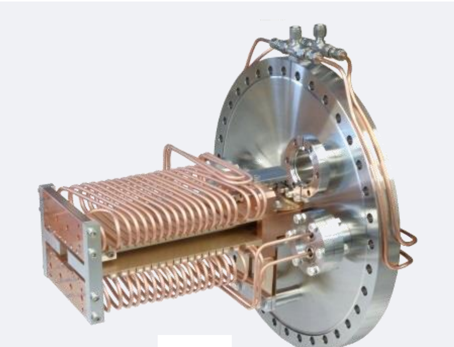
RF Bellows

In air insertion devices





photon absorbers

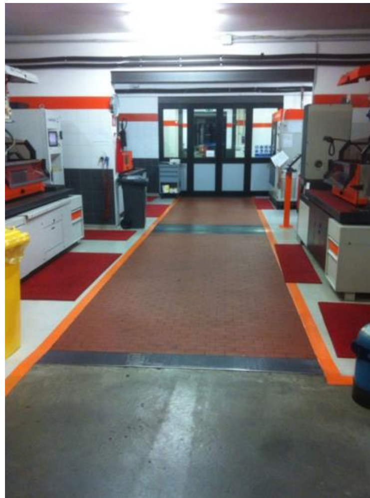


Taper

saes high vacuum

SAES RIAL Vacuum manufacturing expertize

- Drilling, turning, CNC machining
- Wire, die sink e micro-hole EDM (electrodischarge machining)
- Laser and TIG/MIG and plasma Welding and marking
- Metrology (faro arm, Zeiss contura...)
- Component /Chambers cleaning and NEG coating (through SAES®)
- Degassing ovens
- CAD/CAM systems



Recent projects: APS-U @Argonne (2020-2023)

- APS (Argonne Photon Source) the largest US synchrotron upgrade
- SRV has been awarded multiple large contracts for the manufacturing of
  - IDVC 5,5 m long aluminum chamber
  - Photon absorbers
  - Inconel chambers (NEG coated)
  - RF fingers
  - Horizonatal collimator chambers
- All the projects are now concluded and chambers delivered


IDVC

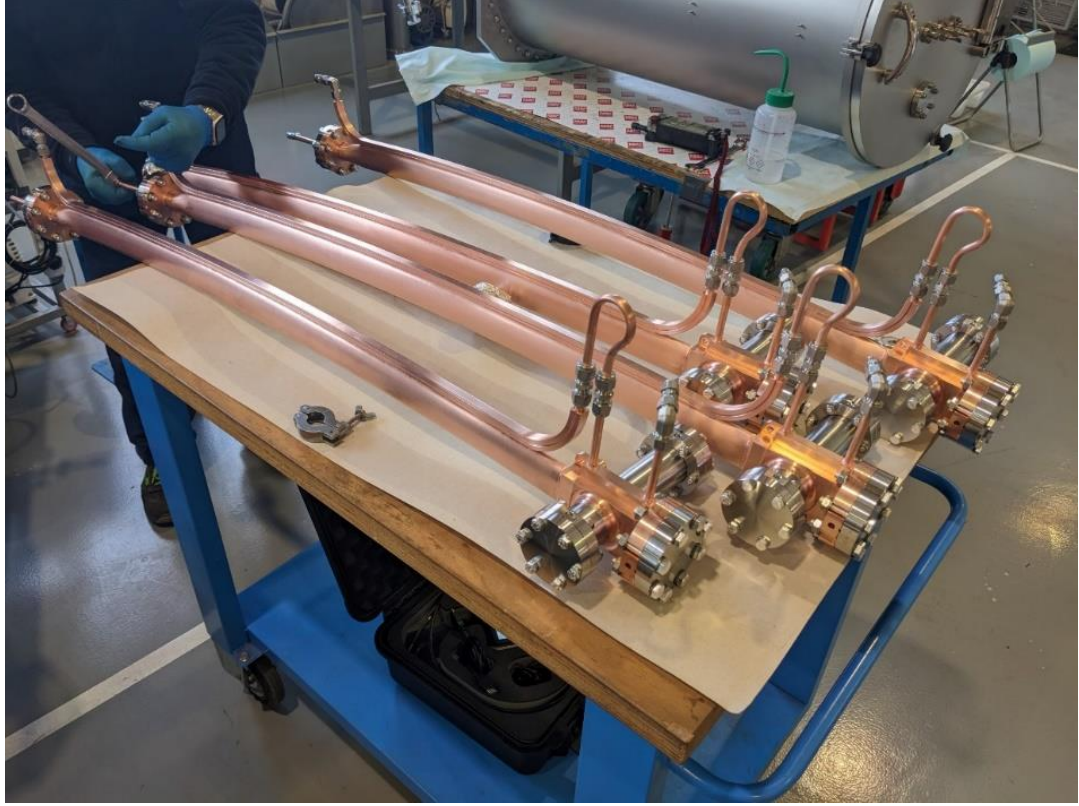

IDVC

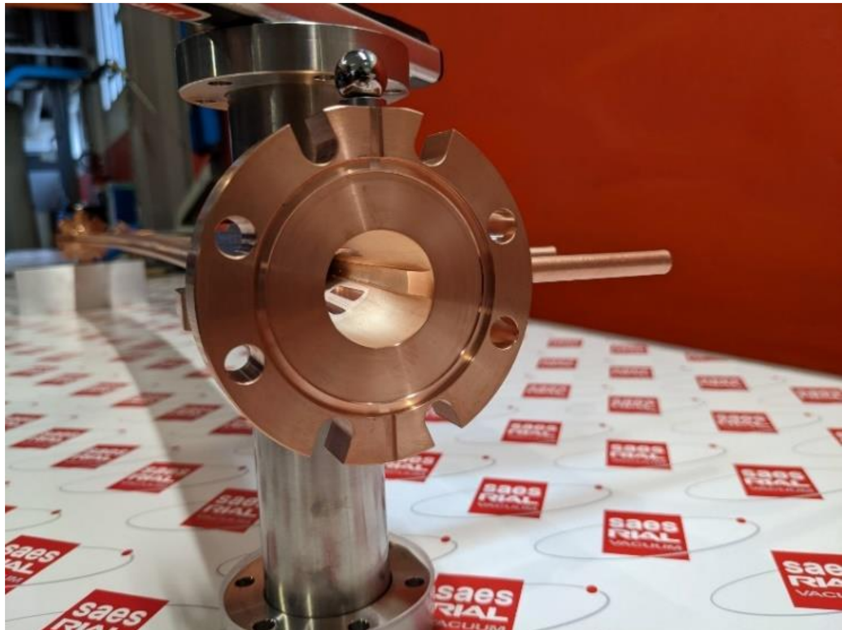

INCONEL

Recent projects:
ALS upgrade@Berkeley (2022-2023)

SRV has been awarded multiple contracts for the manufacturing of

- NEG coated Dipole copper chambers
- Multipole copper chambers
- Complex chambers

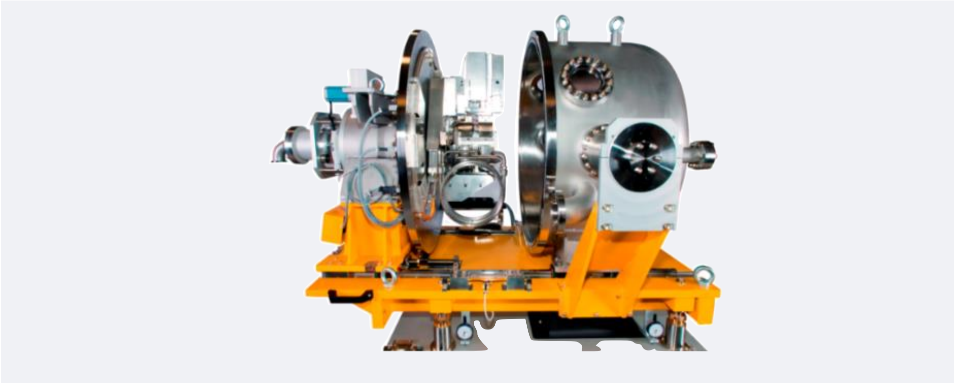




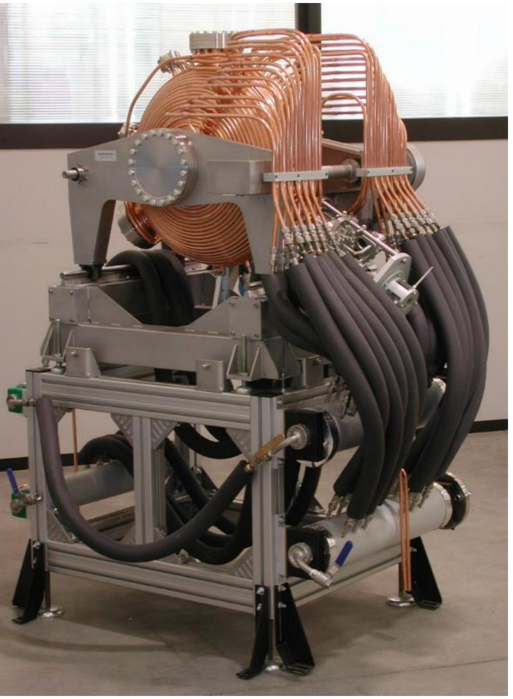
Strumenti Scientifici Cinel

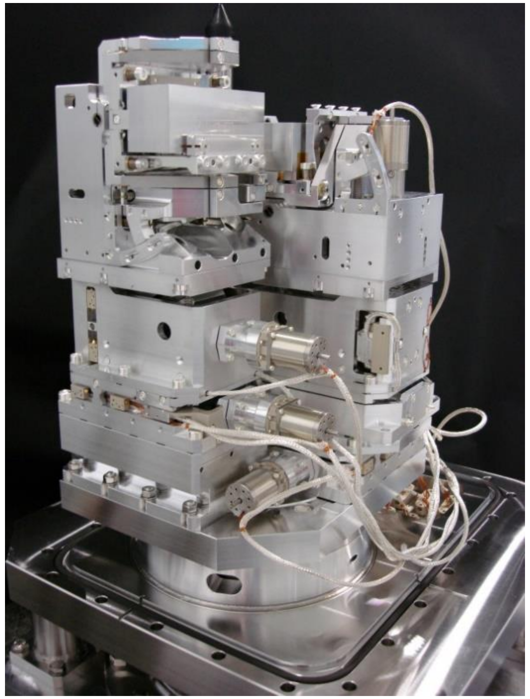
- Established in Vigonza (PD) in the 70s. Cinel quickly becomes a leading company in the design and manufacturing of components, systems and scientific instrumentation for accelerators.

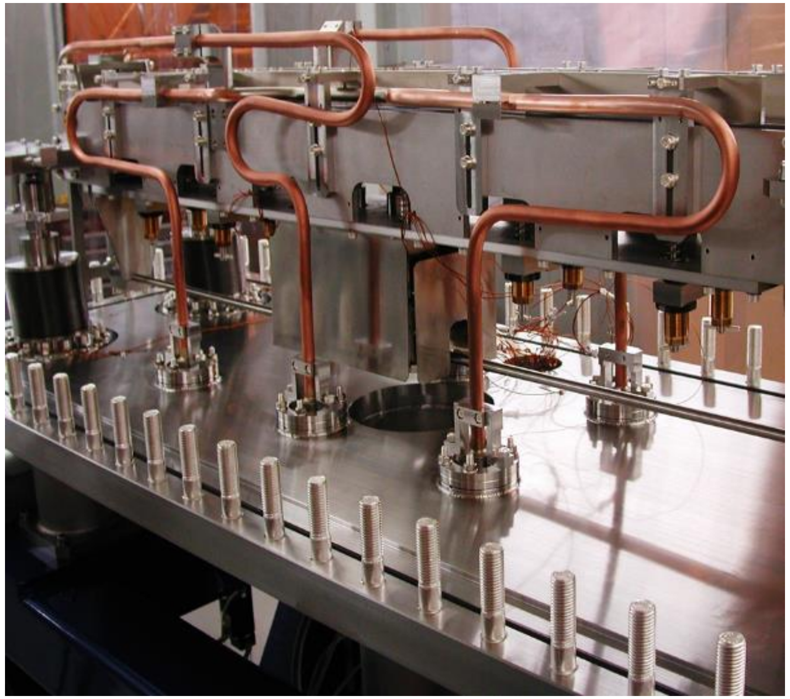
- Based on 3 plants for a total of 3500 m^2 with distinctive competences:
  - 3D CAD mechanical design and system integration
  - High precision CNC machining
  - EDM machining
  - TIG, MIG & MAG welding, brazing oven
  - Cleaning baths
  - Clean area for assembly
  - Metrology
  - Vacuum testing
  - **Since July 2021 it fully belongs to SAES® Group**

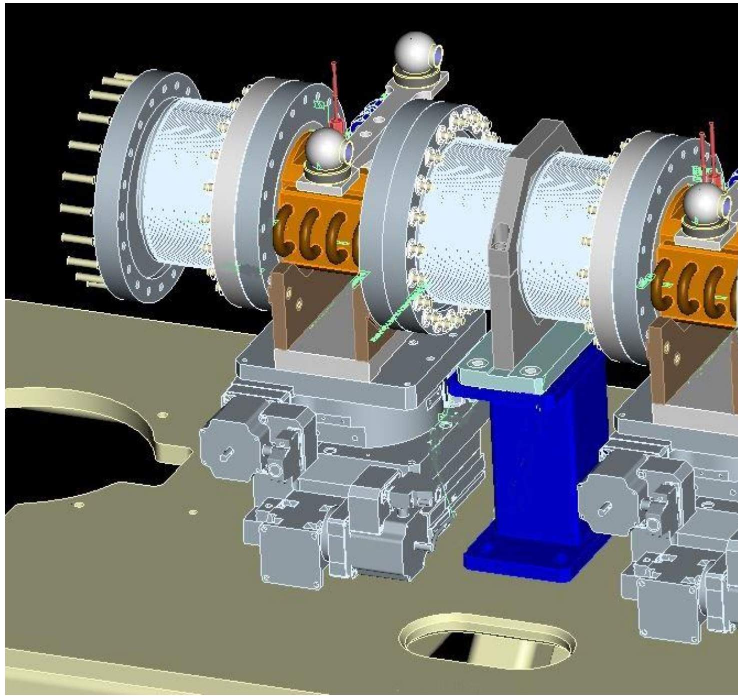


Cinel: BL and instrumentations for accelerators



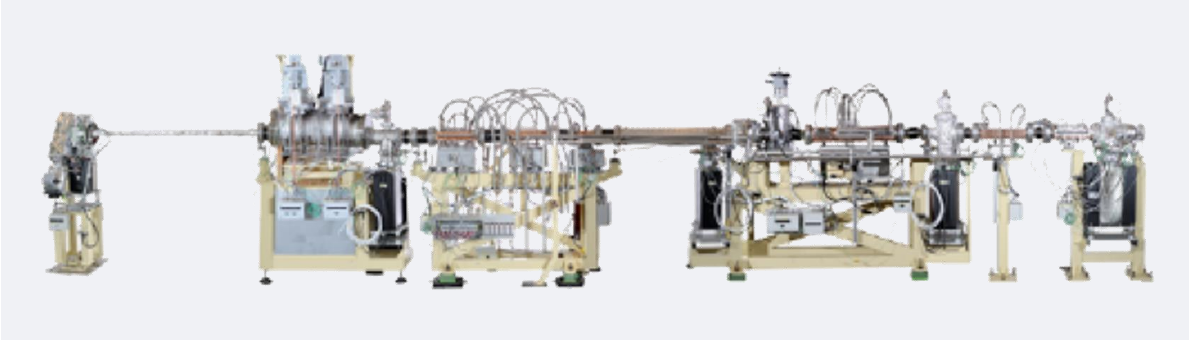


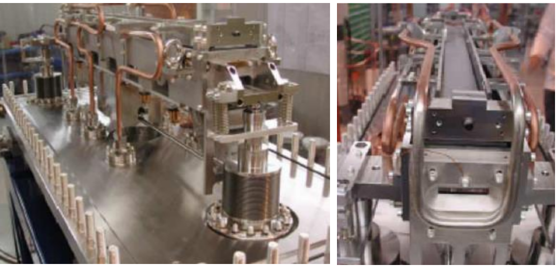




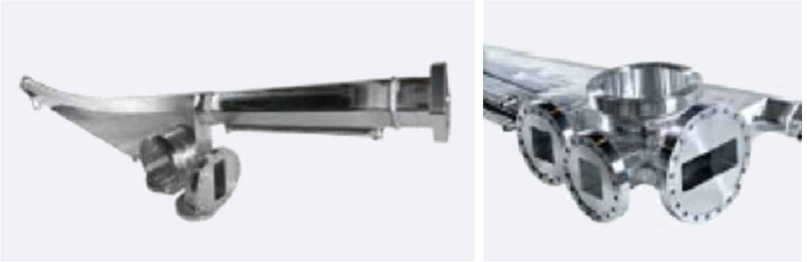
Cinel: BL and instrumentation for synchrotrons

120 Canted Wiggler Front-end
Diamond Light Source Didcot (UK)

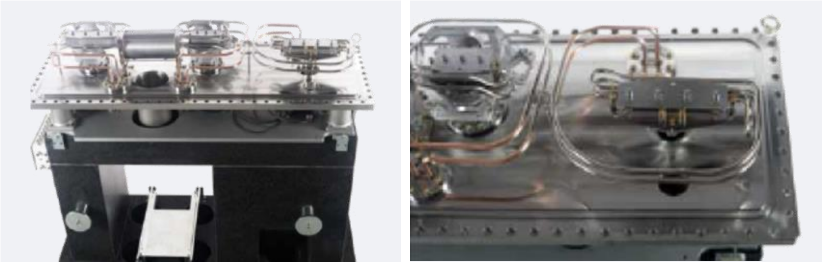




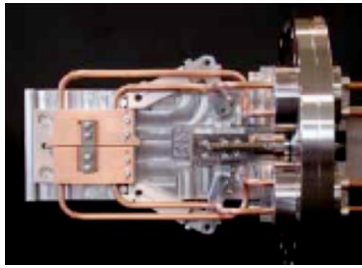
Mirror chamber for Protein Cristallography Beamline (M1)
XOoDA Swiss Light Source SLS Villigen (Switzerland)



Vacuum Chamber
Elettra Synchrotron Laboratory Trieste (Italy)



Mirror chamber for X-ray Deimos Beamline
Synchrotron Soleil Saint-Aubin (France)

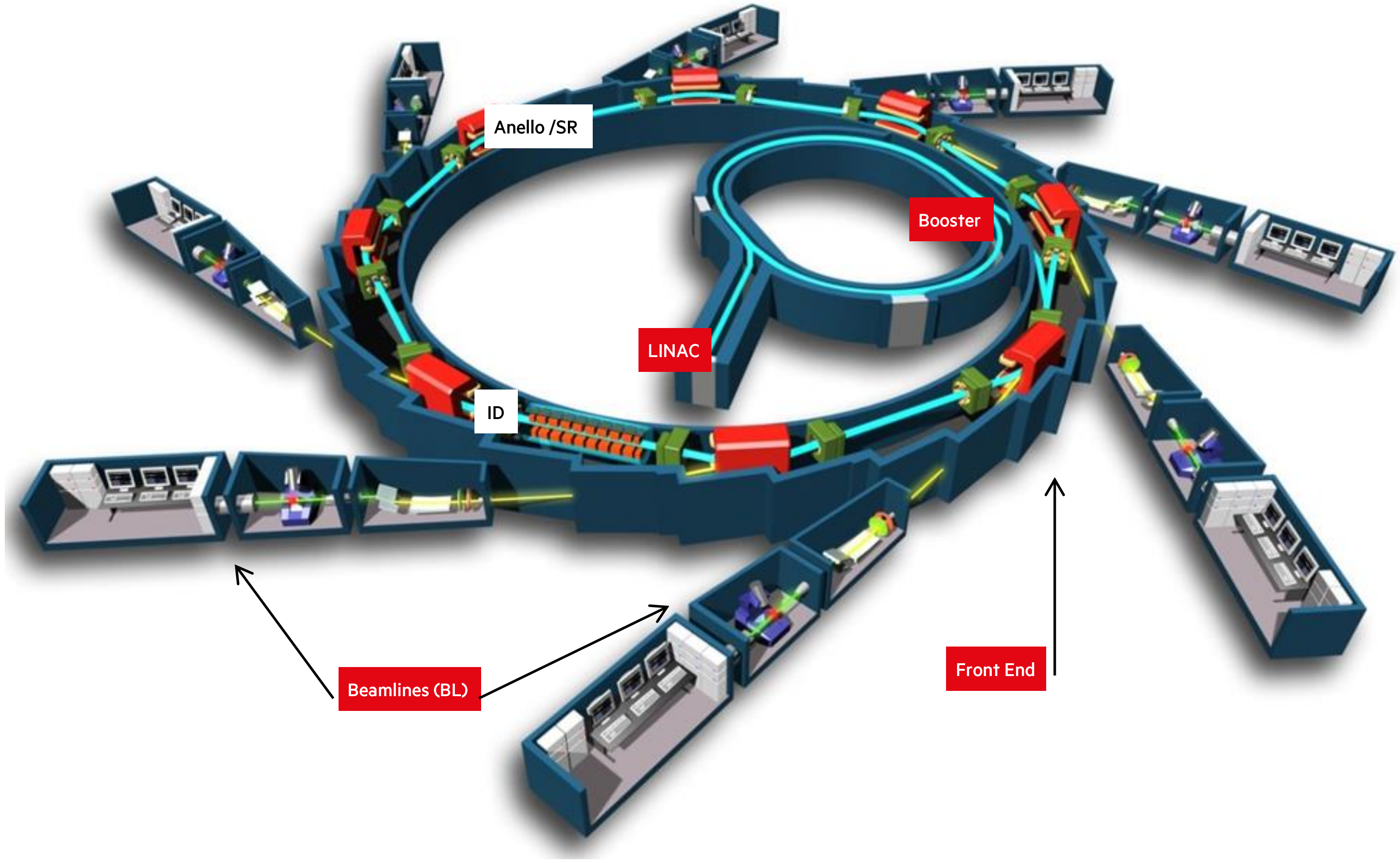


High Precision Water Cooled Slit
Canadian Light Source-CLC
Saskatchewan University (Canada)

The accelerator market

- Through
  - NEG and Vacuum technologies
  - SRV
  - Strumenti Scientifici Cinel

- SAES Group can offer
  - Broad product and solutions portfolio
  - NEG pumps
  - Vacuum chambers
  - Single instruments
  - Complete beamlines



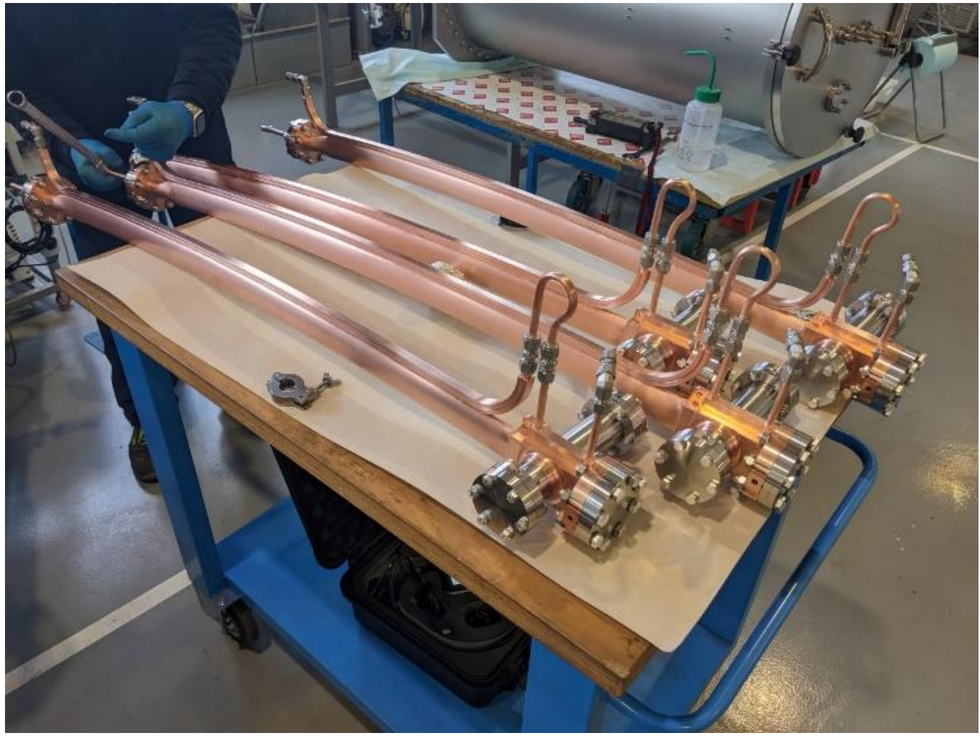
Integration process

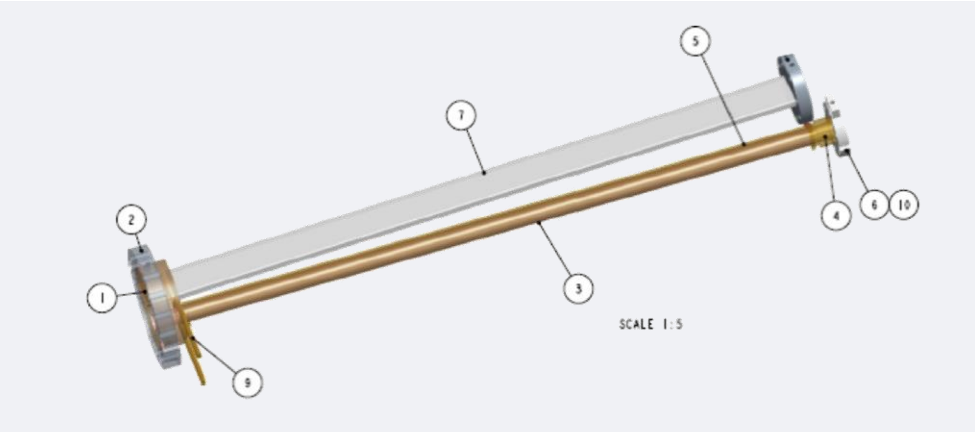
To improve alignment and synergies within the Division a significant number of actions were already taken since the past year

- Cinel and SRV are implementing the same ERP system
- Investment for capital equipment are evaluated at the Division level
- Periodic meetings are held within the Division to align all parties' activities
- In case of tenders only one company within the Division will submit an offer
  - For the supply of pumps: SAES Getters®
  - For vacuum chambers Cinel or SRV, depending on the specific expertize, core technologies, past experience, available capacity and overall competitiveness
  - For beamline instrumentation: Cinel
  - When requested, SAES Getters® will provide the NEG coating to SRV or Cinel at I/C prices

Past examples

- 200 NEG coated Inconel chambers delivered to APS U
  - Chambers produced and cleaned by SRV
  - NEG coating by SAES®
- Multipole and dipole chambers for LBNL
  - Manufacturing and cleaning by SRV
  - Fine machining and brazing of the pumping block by Cinel .
  - NEG coating done by SAES®.
- Prototypes chambers 3-4 &6 for DLS II
  - Manufacturing by Cinel
  - Cleaning for NEG coating by SRV
  - NEG coating by SAES®
- Many Others supply and collaborations (SOLEIL, PSI, ELETTRA, KEK, GSI, EIC, TRIUMF, …)





Thank you for your attention

saes

www.saesgroup.com