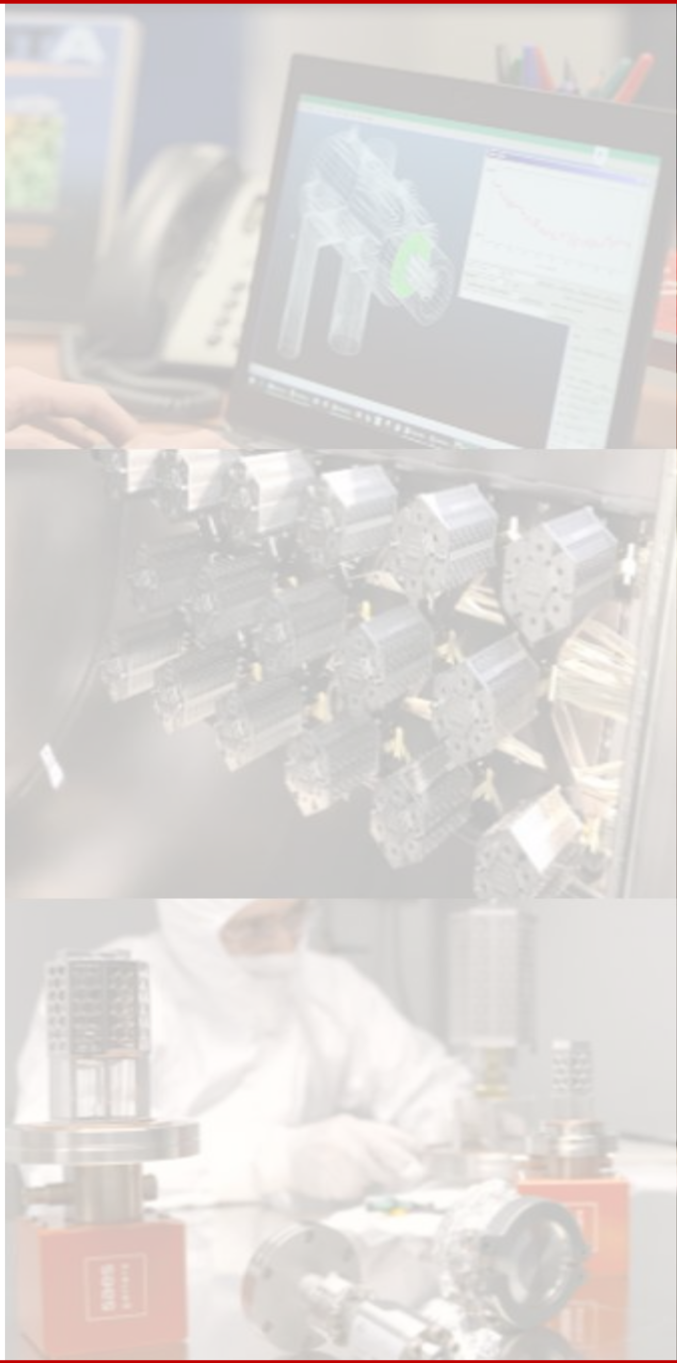
ZAO NEG Technology in Fusion Energy Applications



Vacuum Technology Division

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Content

- Vacuum Systems Challenges in Fusion Energy
- ZAO NEG pumps characteristics in Fusion Energy
- Applications
- NEG basics
- Conclusions
- New vacuum trends

Content

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Thermonuclear Fusion: a new promising and powerful energy source

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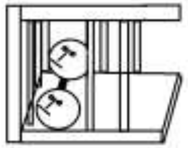
Fusion Energy is based on the thermonuclear reaction of **hydrogen isotopes** fuels in a plasma



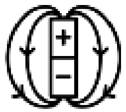
In stars, the huge gravity allows **confining** atoms and to produce energy by fusion at about 15 million °C

The **thermonuclear reactors** developments started in 50's-70's to reproduce the energy production mechanisms inside stars

The most promising fusion reaction on earth involves D and T to produce He and highly energetic neutrons

To get the confinement and plasma process of H_2 isotopes in thermonuclear reactors, 3 main aspects must be fulfilled

- Make the reaction in **vacuum** (backgound pressure at least 1e-5 Pa)
- Utilize **refilling** sources of H_2 **isotopes and pump exhaust** to keep stable plasma
- Use of powerful **magnets** to confine the plasma



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Vacuum Systems Challenges in Fusion Energy

- The **vacuum** characteristics of fusion energy process in **stars** vs **thermonuclear reactors** are
  - **In thermonuclear reactors vacuum** conditions must be **generated from scratch**
  - H_2 **isotopes** are **confined** by **gravity** inside **stars**, in **thermonuclear reactors** H_2 **isotopes repulse** each other and **escape** from the plasma
  - Escaped isotopes can destabilize plasma process and therefore production of energy
  - The pressure has to be **kept constant** against a certain re-fuelling rate of H_2 isotopes

- In the **vacuum systems** of **thermonuclear reactors**, **2** different **aspects** must be addressed
  - **Base pressure** in high vacuum level, e.g. **at least 1e-6 Pa**
  - **Large pumping speed for** H_2 **isotopes** to either keep **stable fluxes** or **absorb escaped** H_2 **isotopes**

- The **thermonuclear** reactors consist of
  - **main vessel** where plasma process occurs and the produced energy is absorbed & distributed
  - **several subsystems** for plasma heating and confinement, and keep adequate vacuum conditions

- **The background gas** are mainly H_2**, water and** CO/CO_2

- **Hydrocarbons** and **air** are **excluded** from the application

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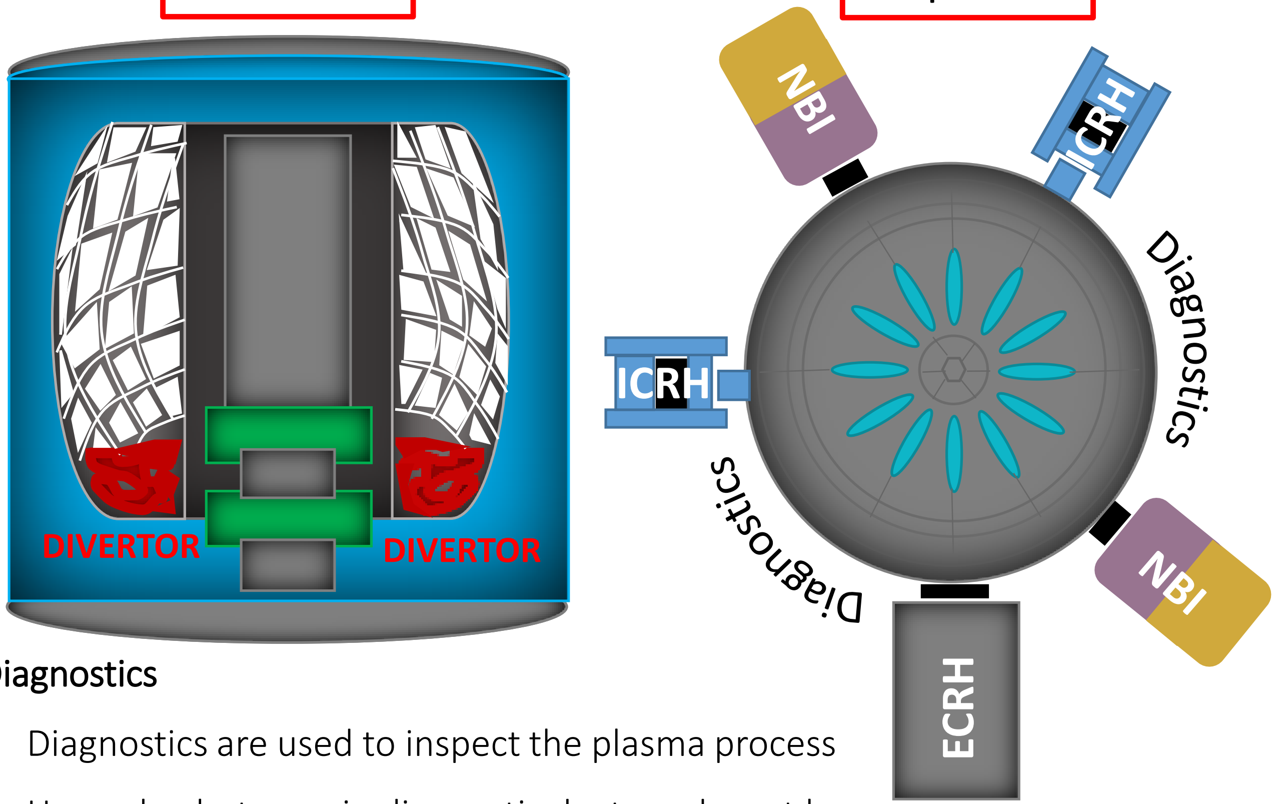
Vacuum Systems Challenges in Fusion Energy: subsystems

Side view Reactor Top view



Diagnostics

- Diagnostics are used to inspect the plasma process
- H_2 can back stream in diagnostic ducts and must be pumped

Storage and release of hydrogen isotopes

- H_2 isotopes are produced and mixed to ^4He
- H_2 isotopes must be selectively pumped and released

Divertor

- The divertor collects the waste of materials used in the plasma process such as H_2 isotopes

NBI

- Neutral Beam of H_2 and D_2 is injected inside the thermonuclear reactor to «heat» the plasma process
- During the experiment, gas is scattered and must be pumped

ECRH/ICRH

- The ECRH/ICRH works in the range of 1e-6 Pa
- Between reactor and ECRH diamond windows can be used to prevent back streaming of H_2 isotopes
- Sometimes, windows are not used and high flux of H_2 can back stream

Vacuum Systems Challenges in Fusion Energy: vacuum requirements

	NBI	Divertor	ECRH/ICRH	Diagnostic	H_2 storage and release
Vacuum background (Pa) - main gas	1e-6 - H_2	1e-6 - H_2	1e-6 - H_2, H_2O	1e-7 - H_2, H_2O	1e-7 - H_2, H_2O
H_2 isotopes level during operation (Pa)	1e-2	1e-3÷1	1e-5	1e-2	1e-2***
Required H_2 isotopes pumping speed (l/s)	10.000÷6M*	10.000÷1M*	Distributed pumping	1.000	NAN****
Required H_2 isotopes capacity (Pa·l)**	10M÷1.000M	1M÷10.000M	2k	10k	NAN****

** The pumping speed depends on NBI and Divertor volumes and Pumps Conductance*

***The required capacity is calculated for 5 days of operation*

****The pressure indicates the H_2 isotopes value at ppb level in He4 gas stream*

*****In the storage and release of H_2 isotopes, NEG "bed" must be considered which can enhance the probability to capture H_2 isotopes in a large gas stream flux*

Takeaways

- In thermonuclear reactors subsystems, the required pumping speed and capacity of H_2 isotopes are very significant
- The required pumping speed and capacity must be considered as distributed inside the vacuum systems
- Given the large amount involved, the pumping system must be able to store and release H_2 isotopes by controlled process

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Vacuum Systems Challenges in Fusion Energy: available pumping technologies

Cryo pump

Ion pump

TMP

NEG pump (CapaciTorr Z400)

	Cryo pump	Ion pump 500	TMP 300	CapaciTorr Z400
Dim. (cm)	20 Ø x 53	52 x 45 x 30	25 x 21	13 x 3.5
Weight (kg)	12	120	20	0.2 kg
Pumping speed for H_2 (l/s)	300	500	500	500
Power consumption (W)	2200	0.035-0.35	35	0

- **Pumping technologies** must be **compared** in terms of **performances vs** (**dimension, weight, pumping speed, Power consumption**)

Vacuum Systems Challenges in Fusion Energy: available pumping technologies

Cryo pump

Ion pump

TMP

NEG pump (CapaciTorr Z400)

Thermonuclear reactor requirements	Ion pump	TMP	Cryo pump	NEG pump
Large H_2 isotopes pumping speed	☹	😐	😐 ☺*	☺
Large H_2 isotopes capacity	☹	NAN	😐	☺
Magnetic field and radiation compatible	☹	☹	☺	☺
Controlled release of H_2 isotopes	NAN	NAN	☹	☺

**It depends on cryogenic temperature*

- **NEG pumps** are **compliant** with main **thermonuclear reactors requirements** in fusion energy applications

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NEG & Fusion Research

- Examples of NEG application in fusion research date back to the 70’s and 80’s
  - 1976 – ASDEX : SORB-AC® cartridges in the ASDEX divertor: study commissioned by the Max Planck Institut für Plasmaphysik (1)
  - 1983 – TFTR Princeton : St101® (Zr-Al) Wafer Modules in the plasma chamber (2)
  - 1986 – JET ICRF : NEG pumps in the Antenna Vacuum Transmission Lines (3)
- More recently, new interest has aroused about the use of NEG in fusion research:
  - 2006 – ENEA Frascati : NEG was used to enable the detection with conventional QMS of 4He / 3He in gas mixtures rich of D2 / T (4)
  - 2014 → DEMO NBI (5)
  - 2018 – LHD at NIFS: installation of a large array of 42 NEG pumps in the divertor completed. Testing is underway (6)
  - 2019 – ITER tested NEXTorr HV200 for the ECRH and first batch of 16 units is used in the first transmission line
  - 2020 – SWISS Plasma Center tested CapaciTorr HV1600 at TCV (7)

(1) M.Borghi and B.Ferrario, Use of non-evaporable getter pumps in experimental fusion reactors, J. Vac. Sci. Technol. 14(1) (1977) 570-574.

(2) J.L. Cecchi et al., Initial limiter and getter operation in TFTR, Journal of Nuclear Materials, 128 & 129 (1984) 1-9.

(3) C. I. Walker, A.S. Kaye, R.A. Horn, F. Mazza, Non-Evaporable Getter Pumping For JET ICRF Antennae, Proceed. 14th Symposium on Fusion Technology, Avignon (France), September 1986 PP. 815-820

(4) A. Frattolillo, A. De Ninno, A powerful tool to quantitatively detect tiny amounts of 4He in a deuterium rich background for fusion research, Proceedings of the 22nd IEEE/NPSS Symposium on Fusion Engineering - SOFE 07

(5) F. Siviero et al., Characterization of ZAO® sintered getter material for use in fusion applications, Fusion Eng. Des. 146 (2019) 1729-1732

(6) G. Motojima et al., New installation of in-vessel Non Evaporable Getter (NEG) pumps for the divertor pump in the LHD, Fusion Eng. Des. 143 (2019) 226-232

(7) M. Baquero-Ruiz et al., Non-evaporable getter pump operations in the TCV tokamak, Fusion Eng. Des. 165 (2021) 112267

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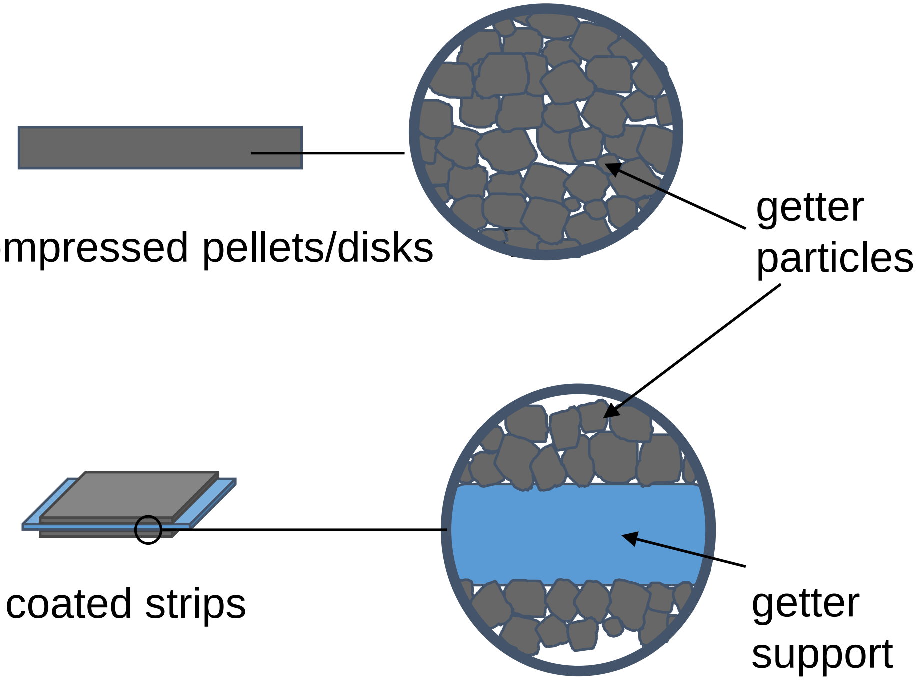
Evolution of NEGs: what's changed from70's to today…

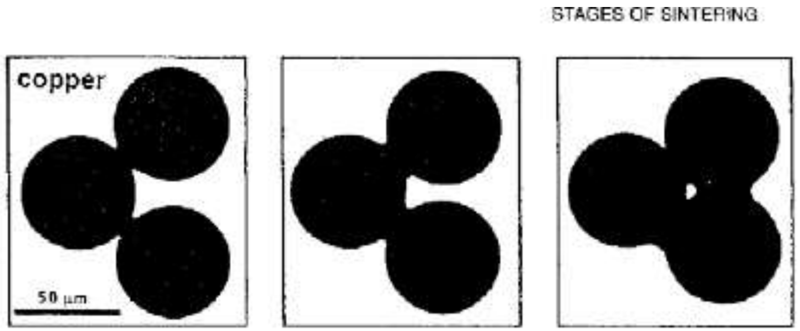
Compressed NEG St707 and St101 on constantan substrate in ASDEX, TFTR and JET



- St707 and St101 have shown a release of particulate after few cycles of H2 regeneration

Porous sintered ZAO disks in LHD, NBI DEMO, ITER ECRH, SPC

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



- Sintering is high temperature metallurgical process (below melting point) to consolidate, by surface melting, powders into a single body.
- In normal applications the aim of the sintering process is to create an extremely dense product, close to what can be achieved by cast melting.
- In the case of a NEG material the objective is just the opposite:

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

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SAES in NEG & Fusion Research

- HORIZON 2020 – TFV project – Sub-project V: Vacuum Systems
  - task 1.3.6 “Development of a NEG-based pumping concept for NBI pumping (NBI)”
- SAES worked with RFX-consortium and KIT at :
  - demonstrating to be able to scale the performance of a “small” pump to a very large one working in conditions relevant for a NBI system
  - building a NEG mock-up of about 45 m3/s for D2 at 1e-2 Pa (2018)
  - Testing at KIT in the TIMO system (2019)
- Objectives
  - Validate models describing:
  - Sorbed quantity Δq [Torr·l/g]
  - Pumping speed evolution S(Δq) [l/s]
  - NEG regeneration: residual q0 , gas quantity extracted, pressure
  - Test pump robustness and performance evolution with cycles
  - Test engineering solutions: mounting and heating, mechanical/electrical design, remote handling solutions, redundancy (ideal target: 10/20y maintenance free system !)
  - Define specific quantities for the use in NBI: pumping speed for pump dimension and weight

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SAES in NEG & Fusion Research

Target Application Requirements

- Large pumping speed for H_2 and its isotopes: several tens of m3/s
- Large gas load : flux up to tens of Pa m3/s, pressure up to 10-2 Pa range
- Hydrogenation-DeHydrogenation (HDH) cycles at several Torr·l/g

Outline

- Why NEG ?
- Pumping properties for H_2 and D_2
- Speed vs pressure
    - Speed vs concentration
    - Equilibrium pressure
    - HDH fatigue test
    - Regeneration
- Towards a full-scale pumping solution
    - Scaling properties from getter disk to small and large-scale pump
    - Working scenarios: matching speed, gas load, duty cycle and regeneration requirements

Why considering a NEG solution?

- High affinity for hydrogenic species
  - pumping speed per unit area
- Large capture capacity for hydrogenic species
  - less frequent regeneration cycles
  - promising system availability
- Passive pump
  - Exempt from faults during operation (e.g power outage: NEG keeps on pumping, no H_2 release)
- Simple integration (vacuum feedthroughs)
  - also improves reliability
  - less design constraints
- RT < Operating temperature < 150°C
  - No issue with stray electrons and radiative heat exchange
  - No freezing of beam line components
- Commercially available product : modularity of NEG elements (disks)
  - Potentiality to build an extremely large tailor-made pump

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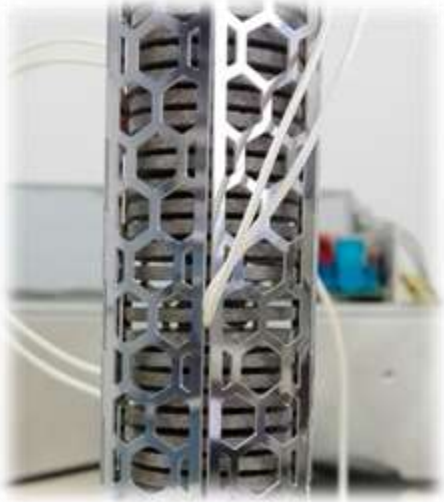
ZAO-HV getter disks

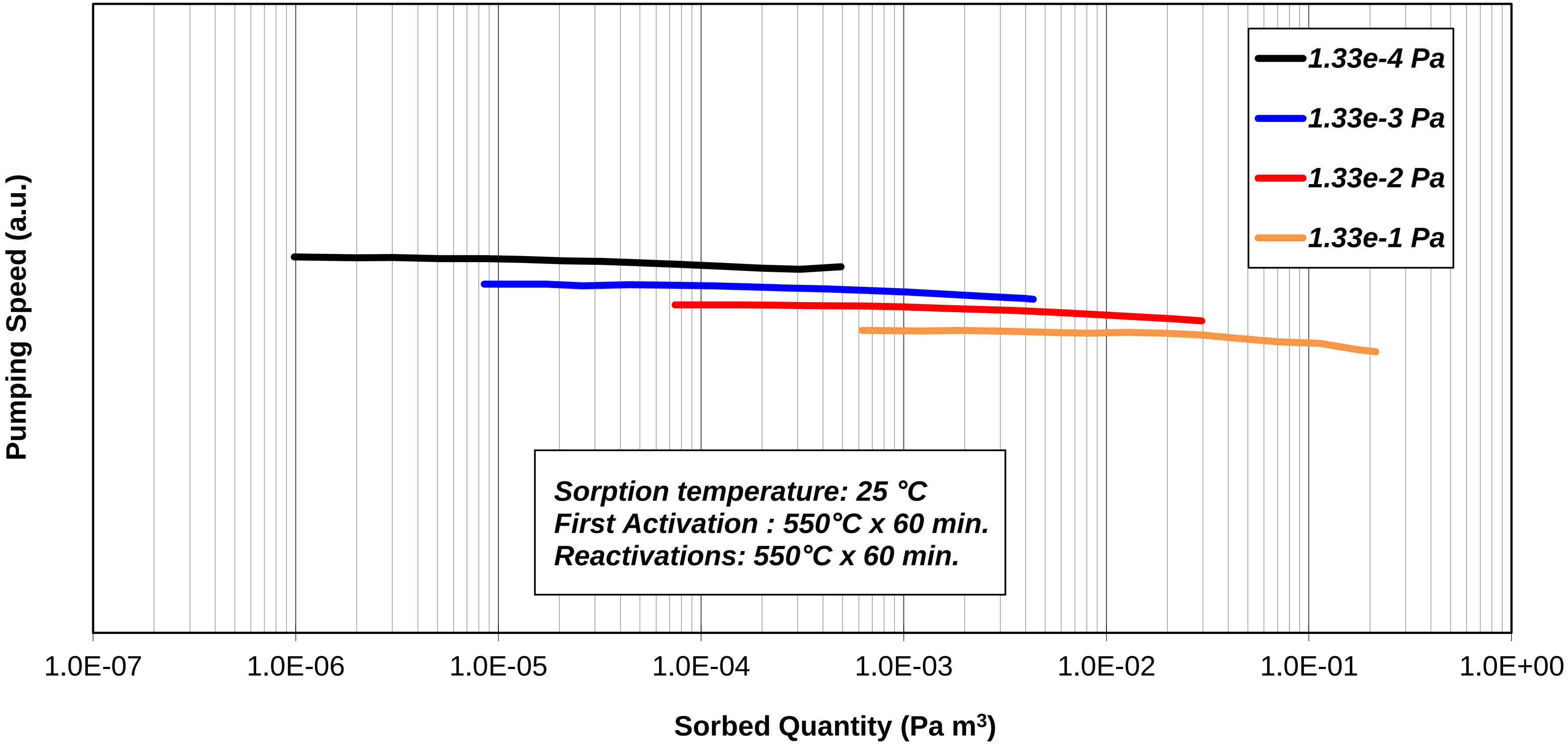
- Proprietary* quaternary alloy : Zr V Ti Al
- Sintered getter: robust and extremely low particle release
- Dimensions:
  - External diameter : ~ 24,3 mm
  - Internal diameter : ~ 6,2 mm
  - Height : ~ 2 mm
  - Weight : 3,5 g
- Standard activation temperature : 450 - 550°C
- Grouped in stacks with 0,5 – 1 mm spacing



** Patented alloy: European patents 2,745,305 and 3,071,720*

Pumping properties of ZAO getter disks

Pumping speed vs sorbed quantity at different pressure of H_2



- H_2 pumping speed of ZAO sintered porous disks shows significant value also at higher pressure values
- 30-40% decrease is measured compared to the nominal pumping speed in the range (1e-4÷1e-1) Pa

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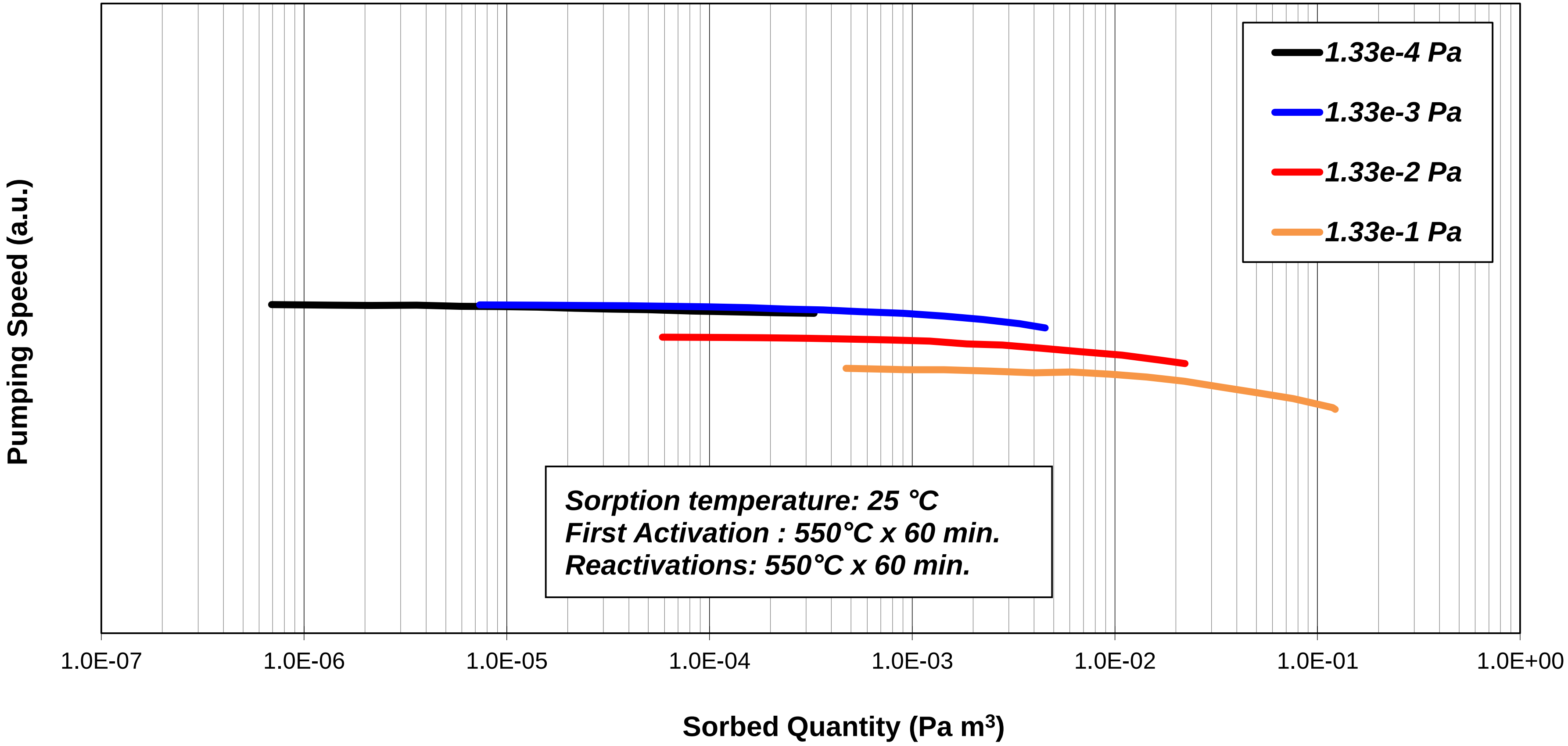
Pumping properties of ZAO getter disks

Pumping speed vs sorbed quantity at different pressure of D_2



- Similar behavior is observed for D_2 at higher pressure values

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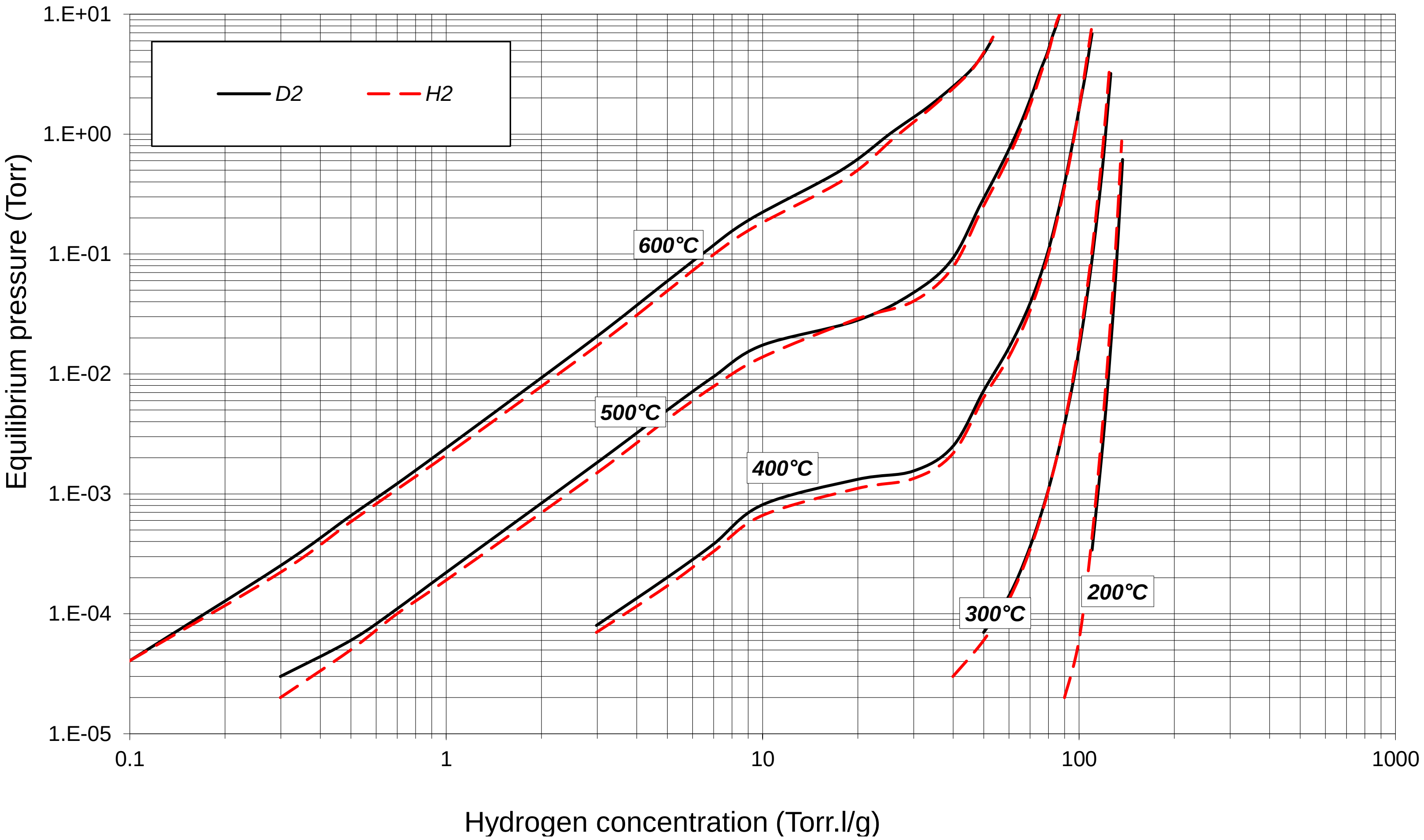
Regeneration mechanism: equilibrium pressure of ZAO getter disks



- Little difference for H_2 and D_2: max 20%
- No hysteresis observed under repeated adsorption-desorption runs

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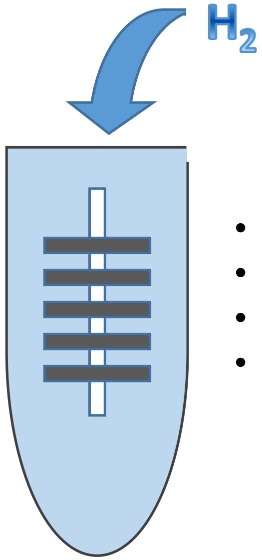
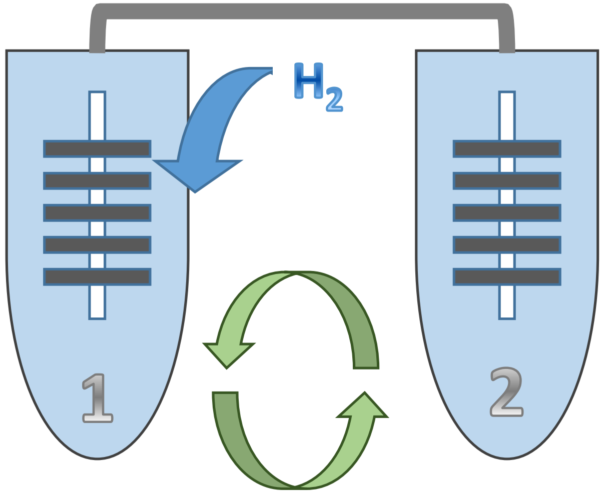
Mechanical properties of ZAO getter disks

- Requirements related to Hydrogen embrittlement
  - "Single shot" limit: dose H_2 until the disks loose particles or cracks appear
  - "HDH" cycle limit: adsorption-desorption cycles at a given concentration



- Dose H_2 (10 Torr·l/g)
- Vibration 33 Hz – 5mm stroke
- Check for dust / cracks
- Next dose

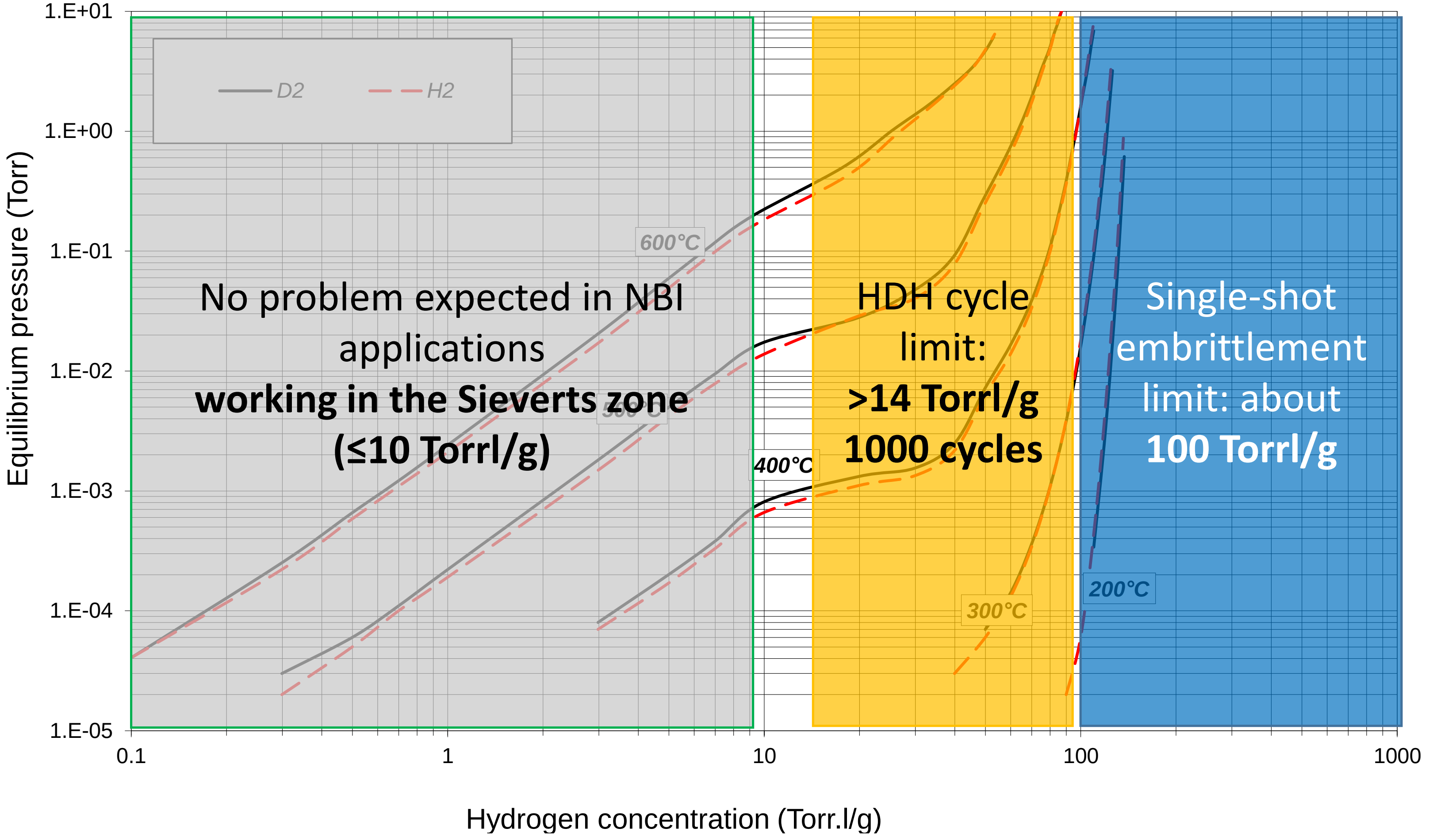
5 disk stack



- **Stack 1** : dose H_2 (15 Torr·l/g)
- **Stack 1** reactivation & **Stack 2** sorption
- **Stack 2** reactivation & **Stack 1** sorption

Mechanical properties of ZAO getter disks

- Hydrogen Embrittlement: ZAO-HV disk are very robust!



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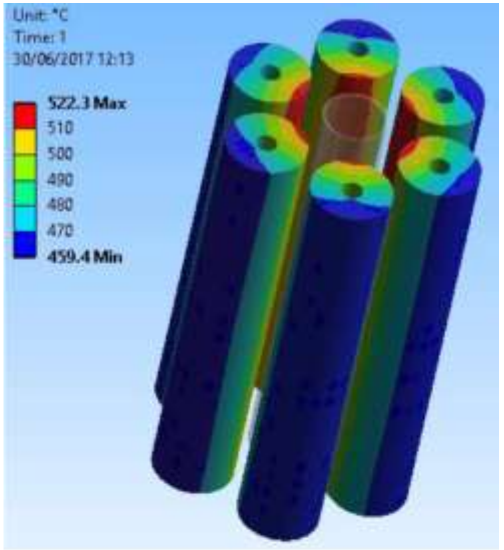
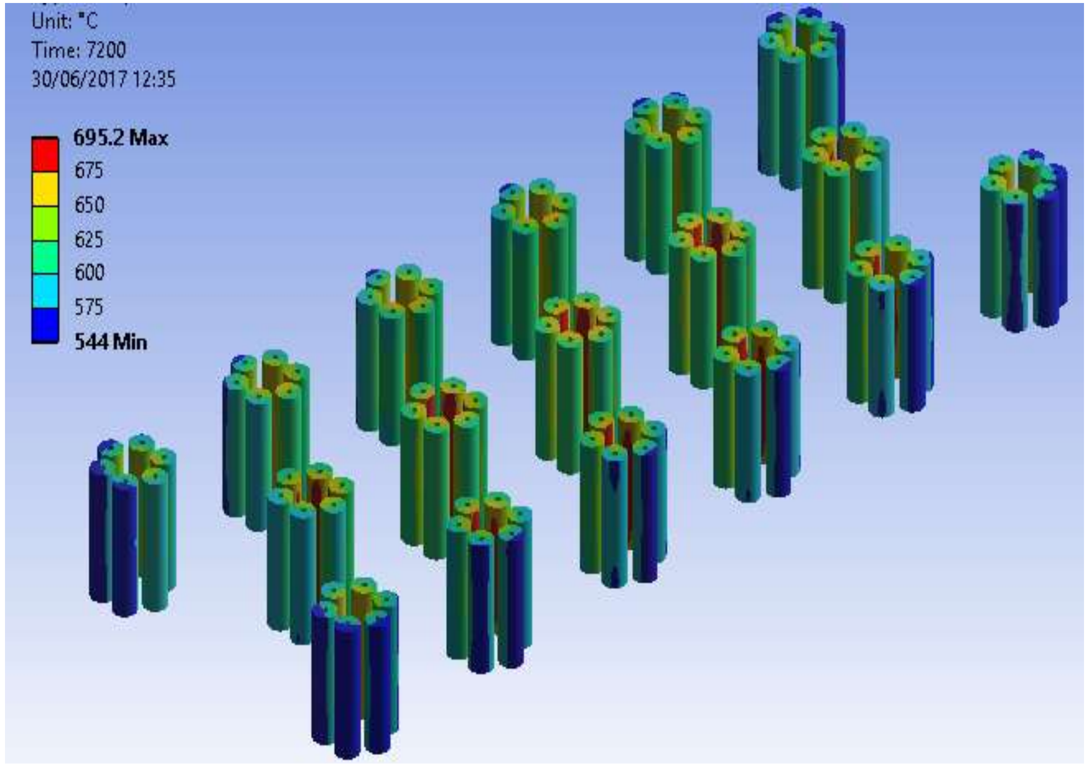
Scaling : thermal

- Case of the mock-up (34 cartridges) already studied by RFX





Activation parameters:
4,8 A, 95V
About 15,5 kW total

Courtesy of E.Sartori, Consorzio RFX

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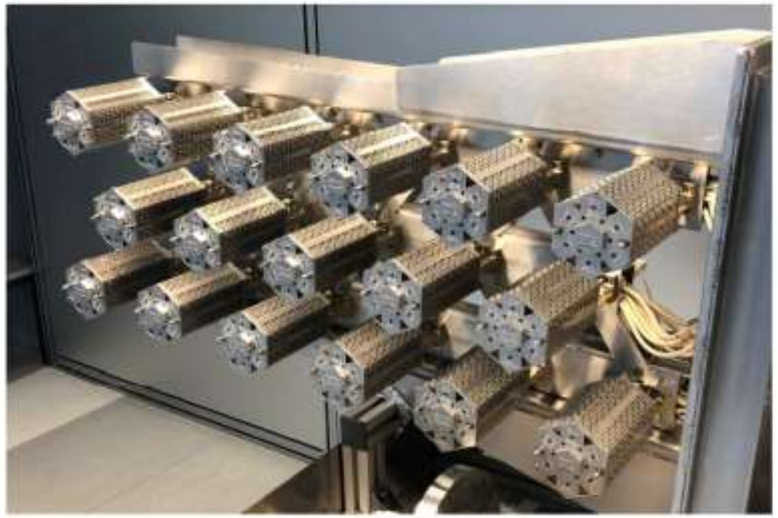
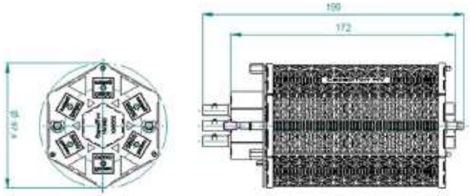
Large pumping speed in fusion energy

- Large NEG pump of 34.000 l/s for H_2 has been developed inside Eurofusion collaboration with RFX and KIT
- The pump has been developed ad pumping system of DEMO NBI
- NEG pump shown stable performonaces
  - After several cycles of sorption/desorption of H_2 and D_2
  - Under different temperature (40-210°C range), pressure (6 – 100 mPa) and load (0 – 11 torr·l/g)



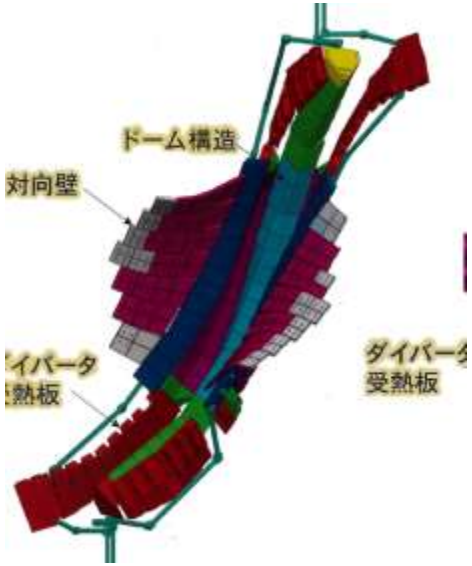
- The cartridges of the mockup were manufactured
- Tests at SAES R&D labs ongoing



- 6 stacks; 270 NEG disks, 920 g
- Heater : Ta wire and alumina support
  - Redundant solution under development

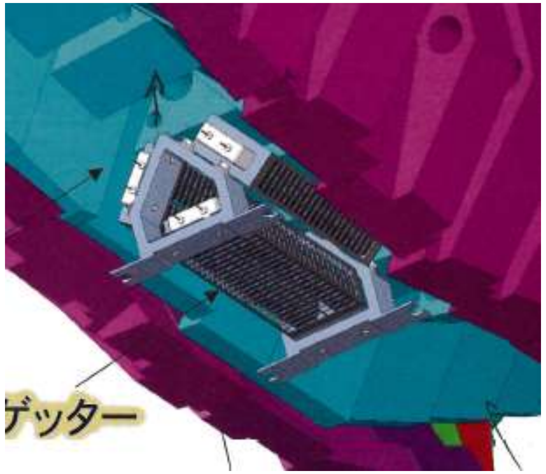
ZAO NEG pump: an extreme flexible pumping system at LHD (NIFS)

Installation region - Divertor



3 NEG wafer modules support

Smart distribution inside the divertor region



- 42 flangeless ZAO wafer modules have been distributed in the divertor at LHD
- The modules are exposed to H_2 injection at a peak pressure in the range 1e-3 ÷ 0.1 Pa

Courtesy of Gen Motojima, engineering and vacuum group at NIFS

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NEXTorr HV 200 @ ECRH ITER transfer line

- NEXTorr HV 200 can keep pressure at 2e-8 mbar in 1.7 m^3 volume chamber
- Leak rate <1e-9 mbar l/sec

Courtesy of Shaun Hughes and David Laugier, ITER organization, Cadarache

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Non Evaporable Getters: Basics

- NEGs are **reactive metals or alloys** which capture active gases, such as H_2O, CO, CO_2, O_2 and N_2 by a chemical reaction on their active surface
- The reaction generates carbides, oxides and nitrides on the getter surface: gases are permanently removed from the vacuum system
- Hydrogen does not react to form a chemical compound but dissolves in the bulk of the getter forming a solid solution
- A getter does not pump noble gases as they do not chemically react

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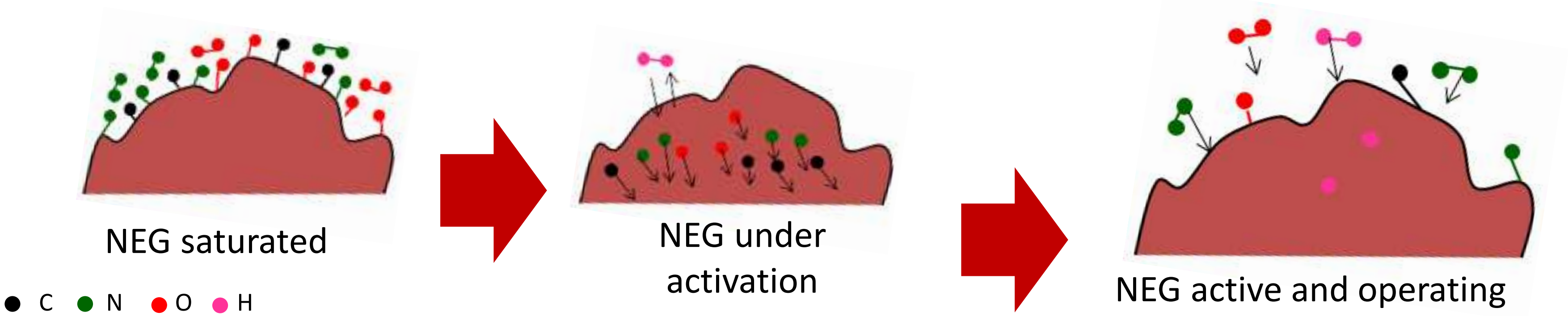
NEG operation

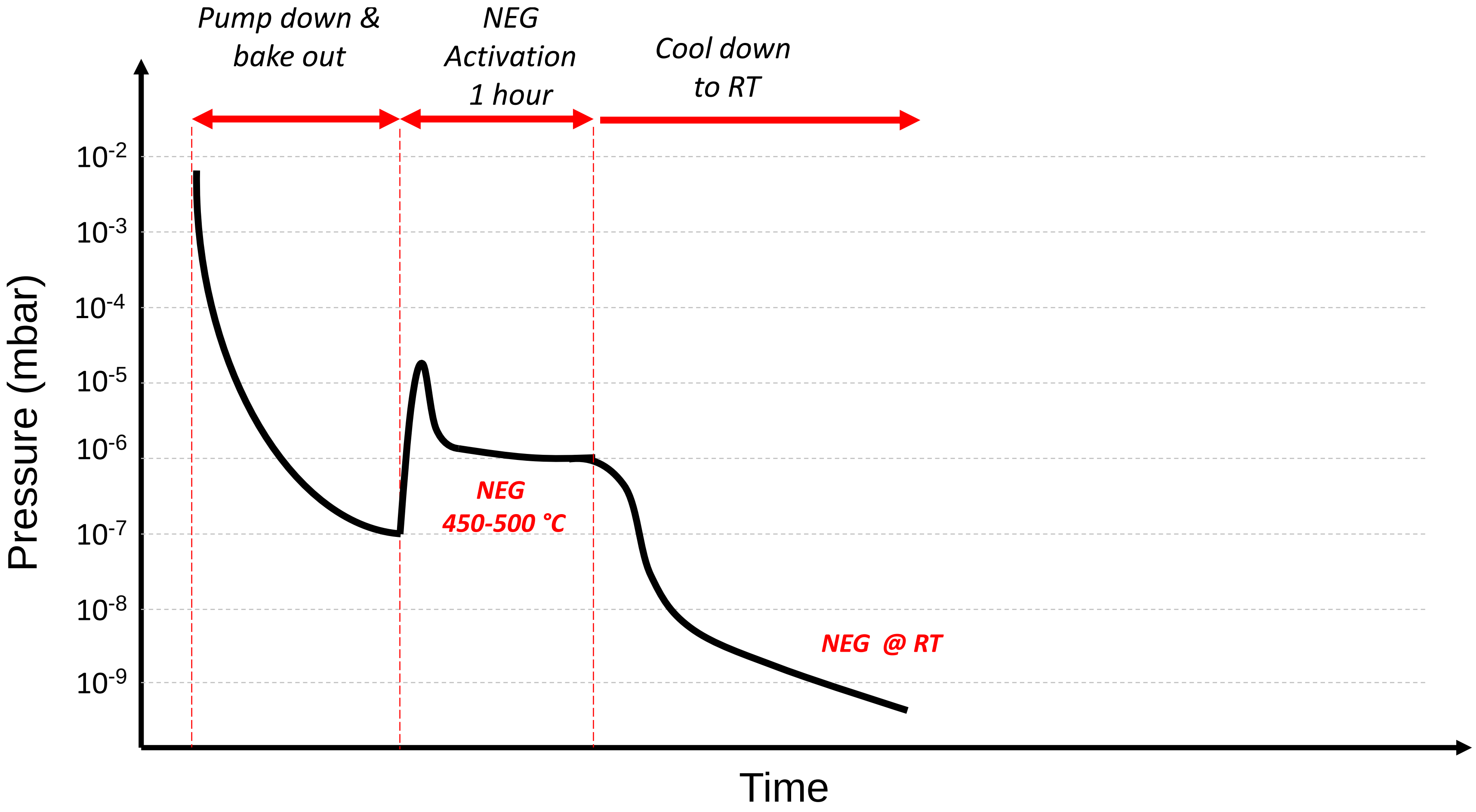
Operating a NEG is simple:

- Step 1: heating under vacuum: ACTIVATION AND REGENERATION
  - ✓ Typically starts at 10^{-6} Torr
  - ✓ **Modest activation temperature**: 40 – 400 W, roughly 500-600 °C
  - ✓ **ACTIVATION**: 60 minutes standard
  - ✓ **REGENERATION**: 5-10 hours depending on experimental conditions
- Step 2: Enjoy!
  - ✓ After the activation or regeneration, the pump absorbs gases at room temperature **without requiring power** (surface absorption)
- When the surface capacity is reached (or after a venting), the pump must be reactivated. Repeatable many times (at least 100)



An example: standard activation

Standard activation of a NEG pump
Regeneration will last longer and will present broader first peak



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Non Evaporable Getter Pumps: When

NEG pumps are the most suited candidate in all those systems where the following requirements need to be fulfilled:

- Clean Ultra High Vacuum (UHV) and more “tough” high vacuum conditions
- High pumping speed for H_2 and all active gases (H_2O, O_2, CO_2/CO, N_2)
- Reduced footprint and light weight
- Passive and constant pumping speed
- Absence of vibrations
- Absence of maintenance
- Reduced or absent power consumption
- Reduced or absent magnetic interference

NEGs are therefore the most suited choice for a wide variety of UHV and high vacuum systems, from research field to industry applications

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Conclusions

- Thermonuclear reactors are promising facilities for clean and powereful energy source
- Reactors and their subsystems need large pumping speed and capacity for H_2 isotopes
- ZAO NEG alloy represents a sutainable pumping solutions with stable and constant pumping performances for H2 isotopes after many cycles of regeneration
- ZAO NEG pumps represents a flexible solution which can be distributed directly inside the fusion energy reactor and its subsystems

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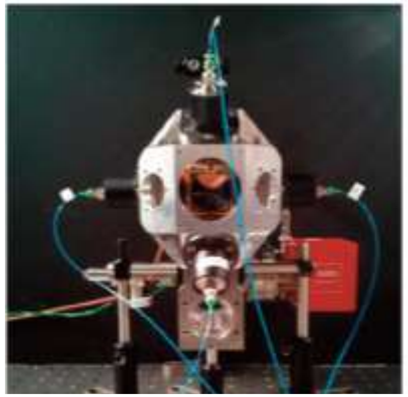
New trends and challenges in vacuum technology

Cold atomic trap



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

Synchrotrons

-Portability of experiment
-high speed/dimension ratio

space applic

Compactness and light

Vacuum Trends

Flexible distribution

high pumping speed

Wide working pressure

MBE - Semicon

Mirror & Monochromator

Interferometer

Large vacuum device requires
-high capacity for all gases
-optimized distribution along the large vessels

Fusion Energy

-More the systems are complex., wider is the operating pressure range
-In complex devices no back out, therefore wide variability vs time

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Non Evaporable Getter adressing new trends in vacuum technology

NEG & Vacuum Trends

Compactness and light

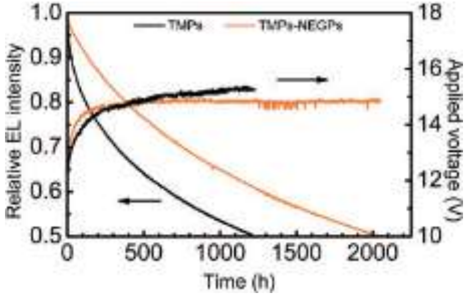
100 l/s in 2.2 kg

Compact distribution @ SWISSFEL

Flexible distribution

CF35 flange 500 l/s

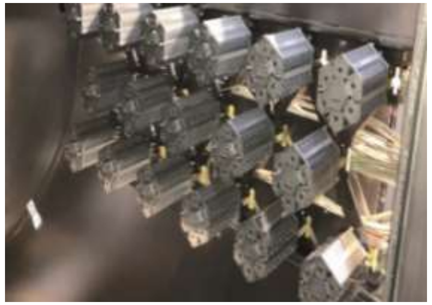
Higher OLED luminescence



high pumping speed

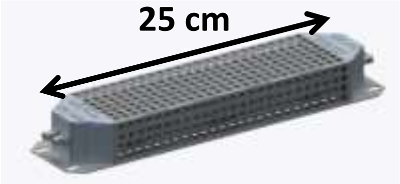
4000 l/s in interferometer

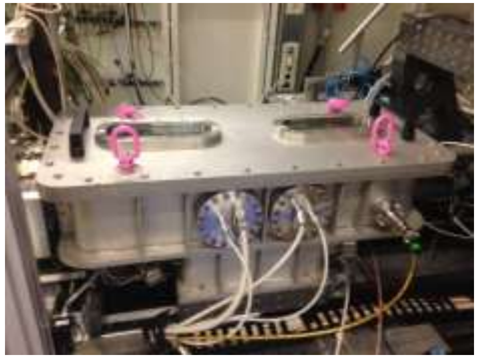
34.000 l/s in 100x70 cm



Wide working pressure

25 cm





Thank you for your attention

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