ZAO NEG Technology in Fusion Energy Applications

Vacuum Technology Division
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- Vacuum Systems Challenges in Fusion Energy
- ZAO NEG pumps characteristics in Fusion Energy
- Applications
- NEG basics
- Conclusions
- New vacuum trends
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Thermonuclear Fusion: a new promising and powerful energy source

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 H₂ isotopes in thermonuclear reactors, 3 main aspects must be fulfilled:

- Make the reaction in vacuum (background pressure at least 1e-5 Pa)
- Utilize refilling sources of H₂ isotopes and pump exhaust to keep stable plasma
- Use of powerful magnets to confine the plasma.
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
  - H₂ isotopes are confined by gravity inside stars, in thermonuclear reactors H₂ 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 H₂ 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 H₂ isotopes to either keep stable fluxes or absorb escaped H₂ 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 H₂, water and CO/CO₂

- Hydrocarbons and air are excluded from the application
Vacuum Systems Challenges in Fusion Energy: subsystems

Diagnostics
- Diagnostics are used to inspect the plasma process
- H\textsubscript{2} can back stream in diagnostic ducts and must be pumped

Storage and release of hydrogen isotopes
- H\textsubscript{2} isotopes are produced and mixed to $^4$He
- H\textsubscript{2} isotopes must be selectively pumped and released

Divertor
- The divertor collects the waste of materials used in the plasma process such as H\textsubscript{2} isotopes

NBI
- Neutral Beam of H\textsubscript{2} and D\textsubscript{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\textsubscript{2} isotopes
- Sometimes, windows are not used and high flux of H\textsubscript{2} can back stream
### Vacuum Systems Challenges in Fusion Energy: vacuum requirements

<table>
<thead>
<tr>
<th></th>
<th>NBI</th>
<th>Divertor</th>
<th>ECRH/ICRH</th>
<th>Diagnostic</th>
<th>H\textsubscript{2} storage and release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum background (Pa) - main gas</td>
<td>1e-6 \cdot H\textsubscript{2}</td>
<td>1e-6 \cdot H\textsubscript{2}</td>
<td>1e-6 \cdot H\textsubscript{2}, H\textsubscript{2}O</td>
<td>1e-7 \cdot H\textsubscript{2}, H\textsubscript{2}O</td>
<td>1e-7 \cdot H\textsubscript{2}, H\textsubscript{2}O</td>
</tr>
<tr>
<td>H\textsubscript{2} isotopes level during operation (Pa)</td>
<td>1e-2</td>
<td>1e-3+1</td>
<td>1e-5</td>
<td>1e-2</td>
<td>1e-2***</td>
</tr>
<tr>
<td>Required H\textsubscript{2} isotopes pumping speed (l/s)</td>
<td>10.000\div6M*</td>
<td>10.000\div1M*</td>
<td>Distributed pumping</td>
<td>1.000</td>
<td>NAN****</td>
</tr>
<tr>
<td>Required H\textsubscript{2} isotopes capacity (Pa\cdot l)**</td>
<td>10M\div1.000M</td>
<td>1M\div10.000M</td>
<td>2k</td>
<td>10k</td>
<td>NAN****</td>
</tr>
</tbody>
</table>

* 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\textsubscript{2} isotopes value at ppb level in He\textsubscript{4} gas stream

****In the storage and release of H\textsubscript{2} isotopes, NEG “bed” must be considered which can enhance the probability to capture H\textsubscript{2} isotopes in a large gas stream flux

### Takeaways

- In thermonuclear reactors subsystems, the required pumping speed and capacity of H\textsubscript{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\textsubscript{2} isotopes by controlled process
### Vacuum Systems Challenges in Fusion Energy: available pumping technologies

<table>
<thead>
<tr>
<th></th>
<th>Cryo pump</th>
<th>Ion pump 500</th>
<th>TMP 300</th>
<th>CapaciTorr Z400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dim. (cm)</td>
<td>20 Ø x 53</td>
<td>52 x 45 x 30</td>
<td>25 x 21</td>
<td>13 x 3.5</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>12</td>
<td>120</td>
<td>20</td>
<td>0.2 kg</td>
</tr>
<tr>
<td>Pumping speed for H₂ (l/s)</td>
<td>300</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Power consumption (W)</td>
<td>2200</td>
<td>0.035-0.35</td>
<td>35</td>
<td>0</td>
</tr>
</tbody>
</table>

- **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

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

<table>
<thead>
<tr>
<th>Thermonuclear reactor requirements</th>
<th>Ion pump</th>
<th>TMP</th>
<th>Cryo pump</th>
<th>NEG pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large $H_2$ isotopes pumping speed</td>
<td>😞</td>
<td>😞</td>
<td>😞</td>
<td>😞</td>
</tr>
<tr>
<td>Large $H_2$ isotopes capacity</td>
<td>😞</td>
<td>NAN</td>
<td>😞</td>
<td>😞</td>
</tr>
<tr>
<td>Magnetic field and radiation compatible</td>
<td>😞</td>
<td>😞</td>
<td>😞</td>
<td>😞</td>
</tr>
<tr>
<td>Controlled release of $H_2$ isotopes</td>
<td>NAN</td>
<td>NAN</td>
<td>😞</td>
<td>😞</td>
</tr>
</tbody>
</table>

*It depends on cryogenic temperature*
Vacuum Technology Division

mak**ing innovation happen, together**

12/11/2021

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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)

(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
(7) M. Baquero-Ruiz et al., Non-evaporable getter pump operations in the TCV tokamak, Fusion Eng. Des. 165 (2021) 112267
Evolution of NEGs: what’s changed from 70’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…
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 $\Delta q$ [Torr·l/g]
    - Pumping speed evolution $S(\Delta q)$ [l/s]
    - NEG regeneration: residual $q_0$, 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
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 H₂ 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
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

- H₂ 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
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
Regeneration mechanism: equilibrium pressure of ZAO getter disks

- Little difference for H₂ and D₂: max 20%
- No hysteresis observed under repeated adsorption-desorption runs
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

- 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!

![Graph showing equilibrium pressure vs. hydrogen concentration for D2 and H2 gases at different temperatures.](image)

- No problem expected in NBI applications working in the Sieverts zone (≤10 Torr/l/g)
- HDH cycle limit: >14 Torr/l/g
- Single-shot embrittlement limit: about 100 Torr/l/g
- 1000 cycles
Scaling : thermal

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

![Image of thermal analysis](image)

**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\textsubscript{2} has been developed inside Eurofusion collaboration with RFX and KIT
- The pump has been developed as a pumping system of DEMO NBI
- NEG pump shown stable performances
  - After several cycles of sorption/desorption of H\textsubscript{2} and D\textsubscript{2}
  - Under different temperature (40–210\degree C range), pressure (6 – 100 mPa) and load (0 – 11 torr-l/g)
ZAO NEG pump: an extreme flexible pumping system at LHD (NIFS)

Installation region - Divertor

- 42 flangeless ZAO wafer modules have been distributed in the divertor at LHD
- The modules are exposed to H2 injection at a peak pressure in the range 1e-3 ÷ 0.1 Pa

Smart distribution inside the divertor region

Courtesy of Gen Motojima, engineering and vacuum group at NIFS
NEXTorr HV 200 @ ECRH ITER transfer line

- NEXTorr HV 200 can keep pressure at 2e-8 mbar in 1.7 m³ 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

- NEG are **reactive metals or alloys** which capture active gases, such as H$_2$O, 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.
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

Pump down & bake out
NEG Activation 1 hour
Cool down to RT

Pressure (mbar)

Time

Pump down & bake out
NEG Activation 1 hour
Cool down to RT

NEG @ RT
NEG 450-500 °C

An example: standard activation
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 $\text{H}_2$ and all active gases ($\text{H}_2\text{O}$, $\text{O}_2$, $\text{CO}_2$/CO, $\text{N}_2$)
- 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.
Conclusions

- Thermonuclear reactors are promising facilities for clean and powerful energy source
- Reactors and their subsystems need large pumping speed and capacity for H\textsubscript{2} isotopes
- ZAO NEG alloy represents a sustainable pumping solutions with stable and constant pumping performances for H\textsubscript{2} 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
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)
- Compactness and light
- Portability of experiment
- High speed/dimension ratio
- Large vacuum device requires
- High capacity for all gases
- Optimized distribution along the large vessels

Synchrotrons
- Mirror & Monochromator
- Flexible distribution

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

Interferometer
- High pumping speed

Fusion Energy
- Future Circular Collider (FCC)
  - Circumference: 500-1000 km
  - Energy: 100 TeV (pp at 350 GeV center)
- Large Hadron Collider (LHC)
  - Large Electron-Positron Collider (LEP)
  - Circumference: 27 km
  - Energy: 14 TeV (pp at 200 GeV center)
- Teravtron
  - Circumference: 0.2 km
  - Energy: 2 TeV (eγ)
Non Evaporable Getter addressing new trends in vacuum technology

- 100 l/s in 2.2 kg
- Compact distribution @ SWISSFEL
- Compactness and light
- Flexible distribution
- 4000 l/s in interferometer
- High pumping speed
- Wide working pressure
- 34,000 l/s in 100x70 cm
- CF35 flange 500 l/s
- Higher OLED luminescence
- 25 cm
Thank you for your attention

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