# Non-evaporable getter pump operations in the TCV tokamak

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## Abstract

A non-evaporable getter pump using the ZAO NEG alloy was installed on TCV and operated during the 2019 experimental campaign. The pump performance, determined from in-situ pumping speed measurements, indicates that current getter pump technologies are well suited to tokamak operations with high power exhaust plasmas, and provide an interesting alternative for applications in fusion experiments.

*Keywords:* Tokamak, vacuum, pump, getter, NEG

## 1. Introduction

Within the context of the divertor upgrade of the Tokamak à Configuration Variable (TCV) [1, 2], an increase of the pumping capacity has been considered to lower the vacuum pressure and provide access to a wider range of divertor regimes.

Several possibilities exist to increase pumping. One, well established, approach is a toroidally-symmetric liquid helium (LHe) cooled pipe in the divertor. This setup, where deuterium gas ($D_2$) is cryo-pumped on the pipe surface, has been implemented in several tokamaks (e.g. DIII-D [3], EAST [4]) and has been shown to be able to provide the high pumping speeds required to affect the vacuum in situations where wall pumping would, otherwise, dominate. The LHe pipe must nevertheless be thermally shielded, and both the shielding and the pipe hidden from direct interaction with the plasma (mostly in the divertor region). Thus, the design would require that a baffled space be built for the pump, which would require a significant modification of TCV with unavoidable conflicts with installed diagnostics. Furthermore, pump throughput would strongly depend on the plasma near the baffled space [5] and on the plasma configuration in general, two conditions that restrict the range of experiments in which the pump would be effective.

Custom-designed cold panels, such as those in AUG [6, 7], or those employing commercial cryocoolers [8], suffer from similar thermal insulation constraints. Commercially available cryopumps, directly installed on existing TCV ports, may cope with the thermal loads, but port availability and shielding from the ambient magnetic fields are a concern. Furthermore, conductance losses due to the port apertures and the connecting elements decrease the effective pumping speed to values that were found to be too low to be of interest.

A compelling alternative technology is non-evaporable getter (NEG) pumps. NEGs do not require a thermal shield and may be installed directly on the divertor walls, which reduces the machine footprint together with conductance losses to the pumping surfaces. Furthermore, they do not require cryogens, simplifying the system design and operation. NEGs have been used in fusion since the 1970s [9], but the getter materials suffered from limitations, most notably due to a lack of robustness to repeated cycles of loading and regeneration [10]. Recently, the development of the ZAO getter alloy [11] has opened new possibilities for experimental applications. For example, a design using several modules with ZAO was recently installed at the Large Helical Device (LHD) [12].

Nevertheless, the environment inside a tokamak is harsh. High magnetic fields, radiation from the plasma (UV, X-ray), high power microwaves for plasma heating and control, vacuum contaminants and energetic neutrals [14] are not found in typical vacuum systems and may have a negative impact on the performance or the NEG integrity. Furthermore, the pumps must handle cyclical gas loads. A demonstration of reliable operations of NEGs (based on ZAO) in tokamak-relevant conditions is, therefore, necessary to establish their suitability for use in the TCV divertor.

In this paper, we investigate the performance of an NEG pump installed in TCV during the 2019 experimental campaign. This constitutes the first test of an NEG pump (using ZAO) during tokamak operations.

The paper is organized as follows. In Sec. 2, we give a description of TCV, its typical vacuum conditions, the installation of the NEG pump, and a description of the pumping speed measurements used to determine its performance. In Sec. 3 we present the results of measurements performed during the TCV experimental campaign and discuss them. Finally, in Sec. 4 we present our conclusions and an outlook on the applicability of the NEG technology in TCV.

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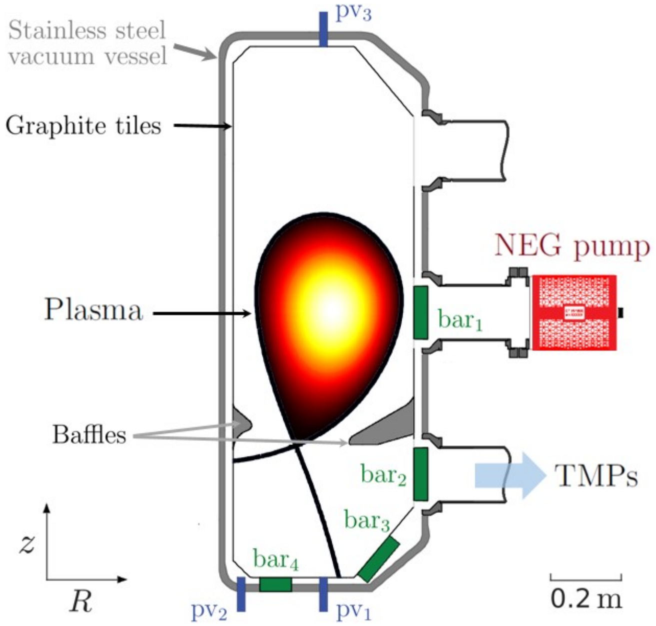


Figure 1: Cross section of TCV showing the elongated stainless steel vessel, the graphite tiles covering the inner wall, the baffles installed for the divertor upgrade and a typical lower single-null plasma (discharge 63676). TMPs are connected to lower lateral ports at four different toroidal locations. The NEG is connected to a mid-lateral port. Also shown, schematically, is the poloidal location of the piezo valves ($pv_{1-3}$) and of the ports leading to the Baratron gauges ($bar_{1-4}$).

## 2. Installation of NEG pump in TCV

A CapaciTorr HV1600 NEG pump, from SAES Getters S.p.A., was installed on a mid-lateral port of TCV (see Fig. 1). The pump required a minor modification in the electrical connections of the getter heating filament to avoid possible ground loops through the tokamak with the filament activated.

### 2.1. *The TCV tokamak*

TCV [13, 14] is a medium size tokamak located at the Swiss Plasma Center in Lausanne. It has a major radius of 0.88 m, a minor radius of 0.25 m, a vacuum toroidal magnetic field of up to 1.5 T (on axis) and a plasma current of up to 1 MA. The inner wall is made of stainless steel with its internal surfaces 90 % covered by graphite protective tiles [15]. TCV has a highly elongated vacuum vessel (see Fig. 1) and unique shaping capabilities that allow studies of plasmas of many different poloidal shapes and different divertor configurations.

Typical TCV discharges have a duration ≈ 2 s and can attain plasma core densities $10^{19} - 2\times10^{20}\,\mathrm{m}^{-3}$, core electron temperatures $\leq$ 15 keV and core ion temperatures $\leq$ 2.5 keV. These hot, dense, plasmas are strong emitters of UV and X-ray radiation [16]. They also emit energetic neutral particles through the plasma edge at energies up to $\sim$ 100 eV [16, 17, 18] or higher, for neutrals arising from charge-exchange reactions with core plasma ions [16, 19].

In addition to ohmic heating, during these experiments TCV could use up to 1 MW of neutral beam heating (NBH) and up to 2.4 MW of electron cyclotron resonance heating (ECRH) at frequencies of 82.7 GHz or 118 GHz. Both the NBH and ECRH systems have planned power upgrades [2].

The typical operation gas is $D_2$. Other gases are sometimes used for impurity seeding, such as $N_2$ in studies of detachment [20], Ne and Ar in experiments to induce or mitigate disruptions [14], and He in experiments such as gas puff imaging. He is also used between experiments for plasma discharge wall conditioning [21]. The fueling and seed gases are injected in the vessel through three piezo-electric valves (Fig. 1) with integrated flow measurement.

### 2.2. *TCV vacuum*

The primary vacuum of the ≈ 4.6 $\mathrm{m}^3$ vessel is maintained by four turbomolecular pumps (TMPs) connected through cylindrical ducts to lower lateral ports (Fig. 1) distributed evenly around TCV. The combined effective pumping speed (seen by the vessel) was measured at $S_{\mathrm{TMP}} = 1700$ L/s for $D_2$. This is sufficient to establish typical residual gas pressures of $4\times10^{-6}$ Pa, albeit only with well-conditioned walls. An extended bake-out and a boronization [21] are required after vessel openings to restore these values.

During a discharge, the neutral pressure typically rises to 1–100 mPa as measured by four Baratron gauges [22] connected at different locations through small vacuum ports (Fig. 1). The measured pressures depend on the plasma configuration and can display significant differences at the four locations [23, 24]. Higher pressures are commonly appreciated in the divertor region for dissipation of charged particle energy and momentum [1], with some detachment experiments [24] reaching divertor pressures as high as ≈ 1 Pa.

Although the TMPs are active during discharges, they only pump a small fraction of the total number of injected particles when a plasma is present. Most of the particles (over 95 % in some experiments) are, instead, pumped by/into the wall [17, 21]. Following a TCV discharge, the piezo-valves are closed and the particles remaining in the vessel are pumped by the TMPs on a time scale of tens of seconds (corresponding to several e-folding times of the pressure).

In experiments with no impurity seeding, most of the gas originates from fueling and recycling of deuterium on the walls [17, 21]. It is therefore expected that the majority of neutral particles near the wall (and in the ports leading to the TMPs) is $D_2$ or D. In $N_2$ seeding experiments [20], $N_2$ and some nitrogen compounds may also be found. Furthermore, hydrogen, oxygen and nitrogen (alone or as molecules/compounds) can be present on the surface of the graphite protection tiles or the remaining metal wall and can be released during a discharge, making it possible for species such as H, $H_2$, CO, $CO_2$ [21], $N_2$, water, methane and ammonia [25] to be found even in experiments without explicit seeding.

### 2.3. *NEG pump*

The NEG works by capturing hydrogen isotopes and *reactive* gases such as $N_2$, $O_2$, water and carbon oxides [26]. The hydrogen isotopes dissolve in the bulk of the ZAO getter forming a solid solution effectively removing them from the vacuum system. The reactive gases undergo chemical reactions with the ZAO surface, forming compounds that stay on the getter surface and effectively remove the gases from the vacuum system. The NEG cannot pump noble gases as they are not chemically active.

We are mostly interested in pumping $D_2$ (Sec. 2.2). As a hydrogen isotope, it is retained in the bulk where there is a large capacity. In fusion applications, the limit for this capacity is related to getter material embrittlement due to fatigue during repeated absorption-desorption cycles. From recent tests [11], ZAO NEG pumps can withstand at least 1000 cycles with loads up to 18.6 mbar L per gram of getter material, which in the case of the CapaciTorr HV1600 [27], yields a limit of 13.8 bar L. Higher loads may not cause immediate damage, but may reduce the number of available cycles (further tests are required). Therefore, it is recommended that this limit must be avoided either by restricting the maximum possible single-experiment load, or by *regenerating* [11, 12] the NEG by a thermal process (typically to around 550 °C) allowing the stored hydrogen isotope to be exhausted. In our experimental setup, we use a regeneration time of ≈ 11 hours. This is a compromise between the pumping speed of the TMPs, the getter temperature and the target final concentration [11]. Shorter regeneration times are possible by adjusting these parameters, for example by increasing the regeneration temperature or the available TMP pumping speed.

The reactive species occupy possible $D_2$ adsorption sites of the ZAO [12, 26] and lead to *passivation*, i.e. a degradation in $D_2$ pumping performance. This happens at comparatively lower loads compared to hydrogenic species. For example, adsorption of ≈ 25 mbar L of $N_2$ is expected to halve the pumping speed of the system when operating at ≈ 180 °C (Fig. 2). This is important as nitrogen and other reactive gases are expected to be present in TCV (Sec. 2.2) or introduced for some experiments. With an average injected $N_2$ load in a seeding experiment of ≈ 5 mbar L, a single seeding experiment may have a noticeable effect on the pumping speed. The NEG performance can nevertheless be reestablished by clearing the getter surface. This can be accomplished with a *reactivation* [11, 12] consisting of a 1 − 3 hour long heating of the getter at 550 °C.

The cylindrical duct connecting the port to the inner vessel has a diameter of 15 cm and a length of ≈ 25 cm. With a typical hydrogen pressure of ≤ 100 mPa, the Knudsen number [28] is Kn ≥ 0.8, indicating a free molecular flow regime (Sec. 2.2). The expected [28] transmission probability of the duct is 0.40 as it has neither gate valves nor other direct streaming obstructions. The duct provides a direct view from the midplane of the inner vessel to the getter cartridges (containing stacks of ZAO disks) mounted inside the pump. Since the plasma particles effectively follow the magnetic field, the cartridges are well shielded from direct plasma exposure.

The nominal pumping speed of the NEG is 1700 L/s for $H_2$ at ≲ 0.4 mPa (Fig. 2). The use of $D_2$ decreases the pumping speed by a factor of ≈ 1.4 (the square root of the ratio of the masses of $D_2$ and $H_2$), and the duct conductance losses (imperfect transmission) reduces it by a further factor of 1/0.40 ≈ 2.5. In the case of higher pressures, there is an extra reduction of up to a factor of 1.7 (at ≈ 100 mPa). The expected effective pumping speed for $D_2$ in typical TCV experiments is thus $S_{\rm NEG} \approx 285 - 500$ L/s depending upon the pressure.

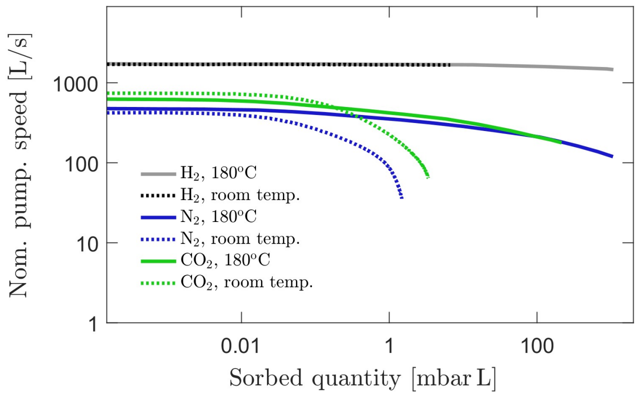


Figure 2: Nominal pumping speed of CapaciTorr HV1600 for different gas loading when operating at room temperature or at ≈ 180 °C. The measurements, performed at SAES Getters, used a gas pressure of 0.4 mPa after a 60 min long activation at 550 °C. Operation of the NEG at 180 °C (solid lines) has little effect on $H_2$ but significantly enhances the capacity for reactive gases, as shown for $N_2$ (blue) and $CO_2$ (green).

### 2.4. Pumping speed measurements

The effective speeds of the vacuum pumps, discussed in Sec. 3, are measured in the absence of plasma. For neutral deuterium at room temperature, wall pumping by graphite is negligible and the total number of (neutral) particles $N$ in the vacuum vessel volume is described by the equation

$$\frac{dN}{dt} = \Gamma_{\rm inj} - \left(\frac{N}{V_{\rm TCV}}\right) S, \quad (1)$$

where $\Gamma_{\rm inj}$ is the injected piezo-valve flow, and $\Gamma_{\rm out} = (N/V_{\rm TCV})\, S$ is the rate of particles that leave through the vacuum pumps of effective pumping speed $S$. Equation (1) assumes that the gas density is uniform throughout the volume $V_{\rm TCV}$. This is reasonable in the absence of plasma as any density gradients are rapidly suppressed by the rapid thermalization of the particles with the wall (through collisions) in the molecular-flow regime. The pressure is

$$p = \frac{k_B T_{\rm TCV}}{V_{\rm TCV}} N, \quad (2)$$

where $k_B$ is Boltzmann's constant and $T_{\rm TCV}$ is the wall temperature. For constant $S$ and no gas injection ($\Gamma_{\rm inj} = 0$), Eqs. (1, 2) predict a pressure that decays exponentially with the e-folding time

$$\tau = \frac{V_{\rm TCV}}{S}. \quad (3)$$

$S_{\rm NEG}$, the effective pumping speed of the NEG for $D_2$, was measured by injecting $D_2$ into the empty vessel and measuring the $p$ decay [12, 29] using the Baratron measurements. The gate valves of the TMPs, the valves of the neutral beam injector and the valves of the reciprocating Langmuir-probe [14] were

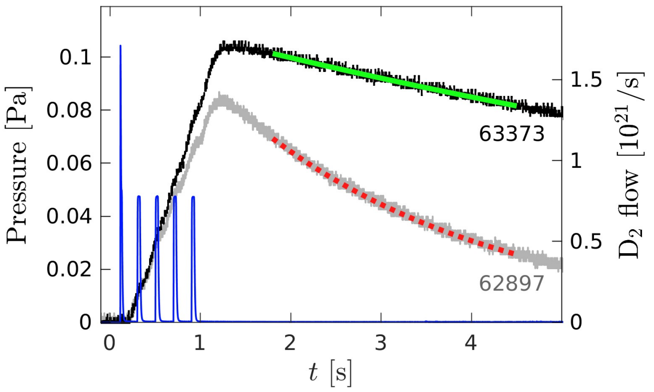


Figure 3: Example of $D_2$ pumping speed measurements. The black trace is the pressure with only the NEG (all TMPs are closed off) for the $D_2$ flow $\Gamma_{inj}$ indicated with the solid blue line. The gray trace is obtained with only the TMPs (the NEG was not installed). A fit of the subsequent exponential pressure decay (green-solid and red-dotted lines), together with Eq. (3) yields $S_{NEG}$ = 370 L/s and $S_{TMP}$ = 1700 L/s, respectively. The numbers under the pressure traces are the corresponding TCV shot numbers.

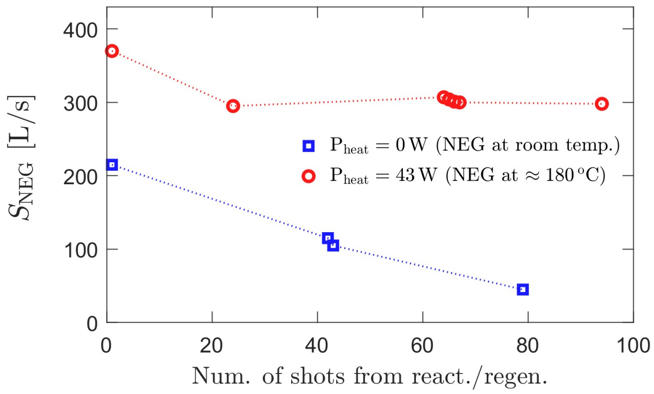


Figure 4: Measurements of $S_{NEG}$. The blue squares are the first set of measurements performed with *no* filament heating. Red circles are measurements with constant low heating. The horizontal axis is the number of the TCV discharge from 63253 (*no* heating) and 63373 (low heating), which correspond to the first experiments after reactivation and regeneration, respectively. The dotted lines are only to guide the eye.

closed as their vacuum manifolds would contribute to pumping. The observed exponential decay of the pressure after the gas injection (Fig. 3) yields the e-folding time and the value of $S_{NEG}$ through Eq. (3).

## 3. NEG pump performance

The NEG was installed near the end of a five month period where the TCV vessel was exposed to air. Upon installation, the TCV vessel was pumped down, baked for ≈ 180 hours at ≈ 230 °C, and then boronized.

### 3.1. *First run at room temperature*

Starting at a residual pressure of ≈ $10^{-5}$ Pa, the NEG was activated (see Sec. 2.3) by powering its heating filament for 90 min whilst employing the TMPs to maintain the vacuum pressure. The power in the filament was ramped during the first 30 min to 370 W (an expected temperature of 550 °C), and was then kept constant for the remaining 60 min.

After activation, the NEG was left to cool to room temperature. TCV operations with NBH but no ECRH then proceeded normally for three days totaling 113 discharges. Figure 4 shows $S_{NEG}$ over this period. The first pumping speed measurement was performed after a 30 min long He glow discharge (see Sec. 2.1), but with no other gas injection or plasma discharge during the 13 hours following activation. $S_{NEG}$ is lower than expected from the NEG specifications (Sec. 2.3), which is probably due to passivation by reactive species in the residual gas or freed during the glow cleaning process. Passivation may also explain the decay of $S_{NEG}$ seen in later measurements, ≲ 25 % of the first value, after only a few days (Fig. 4).

### 3.2. *Experiments with low heating*

For the next set of experiments, the NEG was regenerated (see Sec. 2.3) by heating its getter to 370 W (550 °C) for 11 hours. The heating was subsequently reduced to 43 W (180 °C) and maintained to promote the diffusion of reactive species from the getter surface to the bulk and, thereby, slow down passivation [30, 31].

TCV operations using NBH then proceeded as normal, with daily measurements of $S_{NEG}$ being performed for a week (Fig. 4). The first value of the series is significantly higher than for the case without heating (Sec. 3.1). The second measurement is ≈ 20 % lower, a change that is suspected to be caused by passivation. All remaining measurements yield values of $S_{NEG}$ consistent with the second, in contrast to the observations in Sec. 3.1 where $S_{NEG}$ continued to degrade over time. All observed pumping speeds in this low-heating case are in agreement with the values expected from Sec. 2.4.

### 3.3. *NEG loading*

The NEG throughput (Sec. 2.4) is $\Gamma_{NEG} = (S_{NEG}/k_B T_{TCV})\, p$. Using the Baratron pressure "bar$_1$" (Fig. 1), through a port at a poloidal location similar to that of the NEG, and $S_{NEG} \leq$ 500 L/s, the integration of $\Gamma_{NEG}$ yields a total weekly load of the NEG of ≲ 70 mbar L. This is more than two orders of magnitude lower than the limit of 13.8 bar L required before a regeneration (Sec. 2.3). The NEG may thus be safely operated for these conditions for months without regeneration. Regenerations may thus be planned on days with no plasma operations, or performed overnight, when needed.

The load computed above, however, does not take into account any uptake between experiments during He glow discharges (see Sec. 2.1). While He is not pumped by the NEG (Sec. 2.3), a fraction of the $D_2$ freed during the glow is. Assuming that the He glow restores the same conditions, all the $D_2$ injected via the piezo valves and the NBH must also be pumped by the TMPs and the NEG. With a total injected $D_2$ during a week of ≈ 1.3 bar L, computed for the week of low heating experiments (Sec. 3.2), we approximate the fraction pumped by the NEG with $S_{NEG}/(S_{NEG} + S_{TMP}) \lesssim 23\%$, which

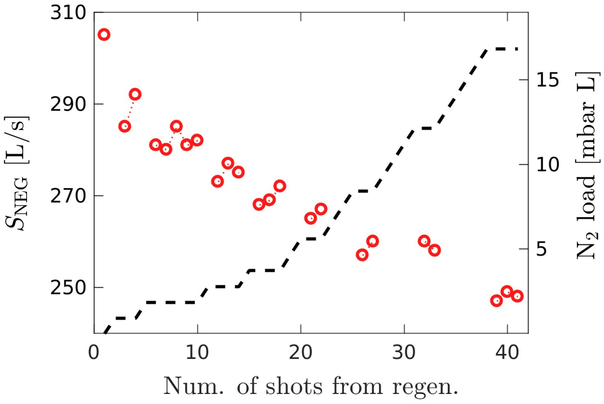


Figure 5: $S_{NEG}$ (red circles, left axis) at different stages of NEG loading with $N_2$ (black dashed line, right axis).

yields $\lesssim$ 0.3 bar L in one week. This is $\approx$ 4 times larger than the estimate of the load computed during the discharges, but still comfortably within operational limits.

### *3.4. Nitrogen injection*

No reactive species (Sec. 2.3) were injected during the week of low heating (Fig. 4), suggesting that their residual presence and the amount freed from the wall degrades $S_{NEG}$ at low heating by not more than 20 % that week.

We performed an additional series of measurements where we injected 1 mbar L of $N_2$ interspaced with $D_2$ (in no plasma conditions), and used the $D_2$ injections, as above, to determine $S_{NEG}$. We used a freshly regenerated NEG with continuous post-heating (180 °C). The pumping of $N_2$ clearly reduces $S_{NEG}$ (Fig. 5). With an average $N_2$ load of 5 mbar L (Sec. 2.3), a typical nitrogen seeding discharge would lead to a degradation of $S_{NEG}$ by approximately 10 % per discharge. Nonetheless, $S_{NEG}$ stays approximately constant with no further exposure to $N_2$, providing a possible way of *throttling* the pump, i.e. to set desired values of $S_{NEG}$ (for $D_2$) without installing a variable conductance baffle (as is often needed with He-cooled cryopumps). Further dedicated studies are required to validate this observation.

Unlike hydrogen isotopes, once $N_2$ (or any other reactive gas) is adsorbed, it cannot leave the ZAO. During reactivations and regenerations, these species diffuse into the getter bulk and remain trapped there. The total $N_2$ capacity is of the same order of magnitude as for $D_2$ [27], imposing a limit on the pump lifetime. For the average $N_2$ loads discussed above, the NEG should withstand $\approx$ 20 bar L/5 mbar L = 4000 nitrogen seeding experiments.

For extended $N_2$ campaigns, however, pumping should be strongly reduced to avoid large uptake of hydrogenic species and reactive gases. This can be achieved by letting the NEG cool to room temperature and then injecting $N_2$. Here $\approx$ 1 mbar L of $N_2$ reduces the pumping speed to a few percent of the nominal value [12] (Fig. 2). The amount of absorbed $N_2$ remains a small fraction of the total capacity of the pump, which allows thousands of passivation cycles. This procedure would be similar to venting of the vacuum vessel ($\lesssim$ 5 times per year), when the NEG material is passivated by $N_2$ and a protective layer is generated that will reduce the deposition of ambient moisture.

## 4. Conclusions

Our experiments demonstrate that the NEG is compatible with TCV operations. The active material (ZAO) is robust to typical tokamak plasma conditions, including a boronization, exposure to radiation from the plasma (UV, X-ray), residual gases, seeded impurities, energetic neutrals and high magnetic fields.

The NEG must operate with continuous low-heating (180 °C). This leads to constant values of $S_{NEG}$ that are consistent with the pump specifications (Sec. 3.2). Using the NEG at room temperature, however, leads to a rapid degradation of the pumping performance (Sec. 3.1).

When degraded, a regeneration of the pump at high temperature can restore the original $S_{NEG}$. Figure 5 shows an example of this, as the initial $S_{NEG}$ was obtained after a regeneration following a vessel opening (and a consequent passivation of the ZAO surface), a boronization and several weeks of TCV operations with NBH *and* ECRH. This also shows that the NEG can withstand high power microwaves.

Particle loading studies show that regenerations may be safely performed once per week (or less frequently), which is compatible with typical run schedules and poses no conflict with standard operations.

To achieve a target pumping throughput of one-fourth the average wall pumping rate in a reference lower single null discharge (Fig. 1) with 330 kW ohmic heating [23], we have estimated (not shown) a required $S_{NEG} \gtrsim$ 5000 L/s for $D_2$, with the pumping surfaces placed near the plasma strikepoints. Assuming negligible vacuum conductance losses from installation directly on the internal wall, we estimate that thirteen SAES HV800 modules [32] can provide the desired $S_{NEG}$. The actual number of modules would be slightly higher once one considers conductance losses from protective structures that would have to shadow the modules from the plasma. This is a significant footprint that would require careful placement in the vessel and a consequent adaptation of an important fraction of the surrounding graphite tiles.

Although the implementation of a particular solution is therefore foreseen to be challenging, these results show that a TCV divertor pumping solution based on NEG pumps may be an adequate alternative to well known cryogenic solutions.

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