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Vacuum calculation of the TBID (Target Beam Instrumentation Downstream) for CNGS

P. Chiggiato

Abstract

For the TBID (Target Beam Instrumentation Downstream) monitor of CNGS (CERN Neutrinos to Gran Sasso) a design identical to that of the TBIU (Target Beam Instrumentation Upstream) monitor of the SPS targets has been adopted. However the vacuum solution implemented in the SPS, namely ion pumping, cannot be trivially applied to CNGS; in fact the high radioactivity level expected for the latter could damage the electrical cables in the about 10 years of expected activity and hinder or delay any human intervention.

In this note the possibility of NEG pumping, without any electrical feeding, is considered. The getter should ensure the demanded pressure limit of 10^{-4} Torr in conditions that are very harsh: temperature up to 150°C , 0.1 A electron bombardment and proton bombardment during the 10 years of working of the monitor.

It is shown that the beam induced CH_4 pumping speed is not enough at the beginning of the operation to ensure the pressure requirements. In addition, in the worst scenario when a uniform electron bombardment is assumed on the entire surface of the electrodes, a huge quantity of NEG strip is needed to pump the total gas load of CO_2 and CO.

An alternative solution is proposed where an ion pump is coupled with St707 NEG strip. In this case the ion pump is necessary only for the first year of operation. After this time the NEG strip can guarantee the vacuum requirement without any additional pumping.

Keywords : TBID, CNGS, Getters, NEG, UHV, desorption, outgassing

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1. INTRODUCTION AND WORKING HYPOTHESIS

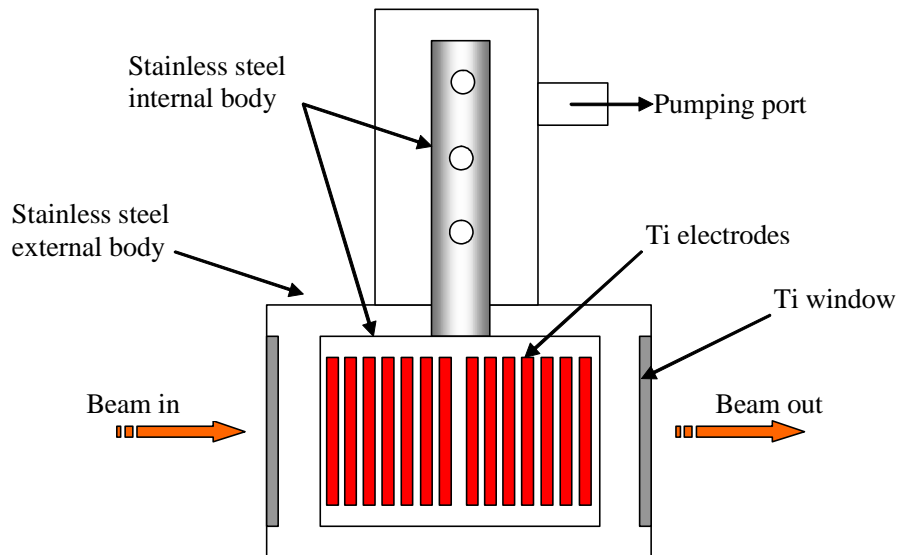
The design of the TBID monitor of CNGS will be very similar to that operating in the SPS, but its pumping solution has to be adjusted to overcome the anticipated high radiation level. Actually, pumping systems requiring electrical feeding are not appropriate since the cables could be damaged during the 10 years of working and their replacement will be prevented or strongly delayed.

NEG (Non Evaporable Getter) materials that could be activated during the bakeout of the monitor provide a valid alternative. For example the Zr-V-Fe alloy, commercially available as pressed powder on constantan ribbon with the trade name St 707, can attain the maximum pumping speed after heating at 300°C for 24 h [1] in vacuum.

With the exception of hydrogen that is dissolved in the bulk, NEG materials retain all the pumped gas on their surface. Therefore, before adopting the NEG pumping solution, the gas load in the monitor has to be estimated to be sure that saturation will not occur during operation.

The assumed working conditions are:

- Working temperature: 150°C. This results from the warming of air around the apparatus.
- Electron bombardment induced by the proton beam: 100 mA, 300 eV maximum energy.
- Ion bombardment: negligible effect on degassing. This presumes that proton at GeV energy will not desorb any relevant quantity of gas in the apparatus.
- H₂ content of the material: about 1 wt. ppm. The stainless steel components are not supposed to be vacuum fired.



The areas of the surfaces exposed to the vacuum environment were roughly estimated and the values used in the calculation are reported in Tab. 1.

PART OF THE APPARATUS	SURFACE AREA CM ²
Internal body	2985
External body	3390
Ti electrodes and supports	7526+3079
TOTAL	16980
VALUE WITH SECURITYFACTOR	20000

Tab. 1: estimated areas of the surface exposed to the vacuum environment

A security factor of about 20 % was applied in the calculation to take into account the surfaces which area is difficult to evaluate (screws, supports, minor modification of design, etc...).

2. CALCULATION

The total gas desorption rate is divided into two contributions. The first, usually known as static outgassing, is the result of the thermal vibrations and will be present during the whole life of the monitor; the second is induced by the proton beam and it consists mainly in electron stimulated desorption from the Ti electrodes.

2.1 Static outgassing

It is supposed that by far H_2 is the main degassed species and that atomic H diffusion from the bulk to the surface is the limiting step.

In this frame, the outgassing rate q is given by eq. 1:

$$q \propto D(T) \cdot f(c_0, T_{th}, t_{th}) \quad [\text{Eq. 1}]$$

where $D(T)$ is the diffusion coefficient for atomic hydrogen at the temperature of measurement, c_0 is the initial hydrogen concentration in the bulk, T_{th} and t_{th} are temperature and time of the previous thermal treatment.

This means that, for similar thermal conditioning of the material, the outgassing rate changes with the temperature as the diffusion coefficient $D(T)$.

In the hypothesis that all the components of the monitor are made of stainless steel, and that the stainless steel is not previously baked at high temperature or vacuum fired, an outgassing rate at room temperature of about $2 \times 10^{-12} \text{ Torr l s}^{-1} \text{ cm}^{-2}$ can be assumed. Therefore, it comes out that:

$$\frac{q(150^\circ\text{C})}{q(RT)} = \frac{D(150^\circ\text{C})}{D(RT)} \rightarrow q(150^\circ\text{C}) = 2 \cdot 10^{-12} \frac{D(150^\circ\text{C})}{D(RT)} = 2 \cdot 10^{-12} \frac{3 \cdot 10^{-9}}{2 \cdot 10^{-12}} = 3 \cdot 10^{-9} \text{ Torr l s}^{-1} \text{ cm}^{-2}$$

and the total outgassing rate is $6 \times 10^{-5} \text{ Torr l s}^{-1}$.

$$\text{The applied relation for the diffusion coefficient is: } D(T) = 5.8 \cdot 10^{-3} \exp\left[-\frac{12870}{R \cdot T}\right] \quad [2]$$

The total H_2 gas load can be evaluated if the weight W of the apparatus is known. Supposing a value of 30 Kg, it comes out that:

$$Q_{H_2} = \frac{10^{-6} W [g]}{2} \cdot \frac{6.02 \cdot 10^{23}}{2.3 \cdot 10^{19}} \approx 400 \text{ Torr l}$$

2.2 Dynamic degassing

The stimulated desorption yield η for electron impinging, with 300 eV kinetic energy, on a stainless steel surface is close to the maximum for this material as shown in Fig. 2

arbitrary unit

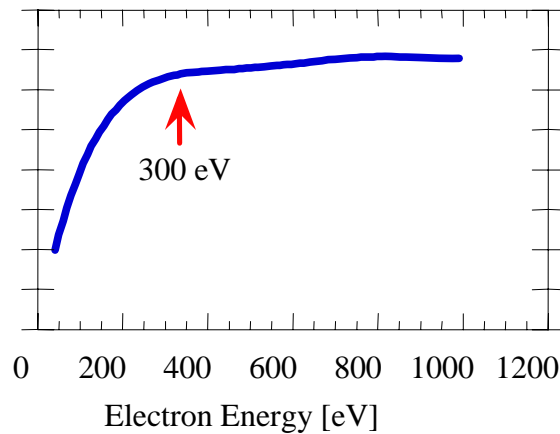


Fig. 2: Electron desorption yield for stainless steel; for 300 eV electrons the value of η is close to the maximum.

The value, which can be easily found in the literature [3], is of the order of 10^{-2} molecules per electron for H_2 , CO , and CO_2 and 10^{-3} molecules per electron for CH_4 as shown in Fig. 3-a and 3-b.

Fig. 3-a shows that the yield of all gases, except water, decreases with increasing dose (cleaning effect). The slope of the curves, in the log-log representation, after about 0.1 C cm^{-2} is roughly constant and the empirical relation $\eta = \eta_0 D^{-\alpha}$ provides a reasonable fit to the experimental data (D being the electron dose per cm^2). The exponent α varies between 1 and 0.6

The dependence of the gas desorption yields on temperature was measured [3] for stainless steel, copper and aluminum, and almost no differences between room temperature and $200 \text{ }^\circ\text{C}$ were recorded.

Data for Ti are similar to those for stainless steel [4] when the baking temperature is less than 300°C ; for higher baking temperatures the desorption yields for Ti are lower (this point will be reconsidered later).

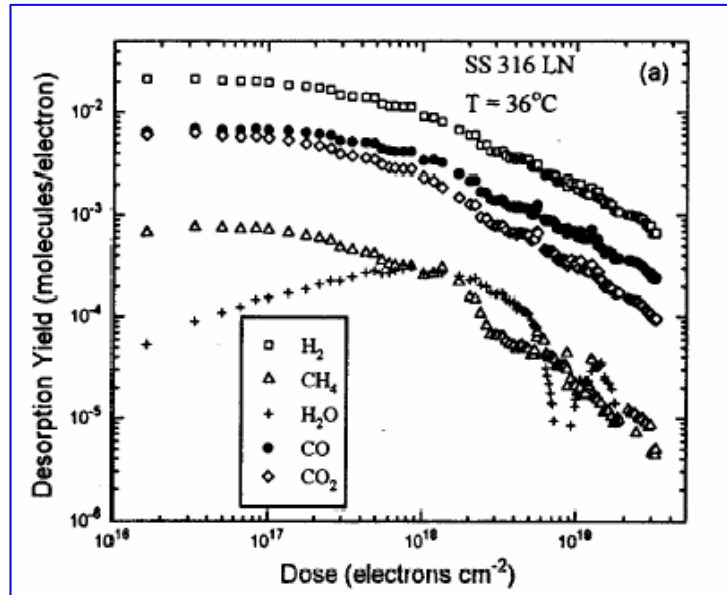


Fig. 3-a: Electron desorption yield for stainless steel for 300 eV electrons as a function of the accumulated electron dose.

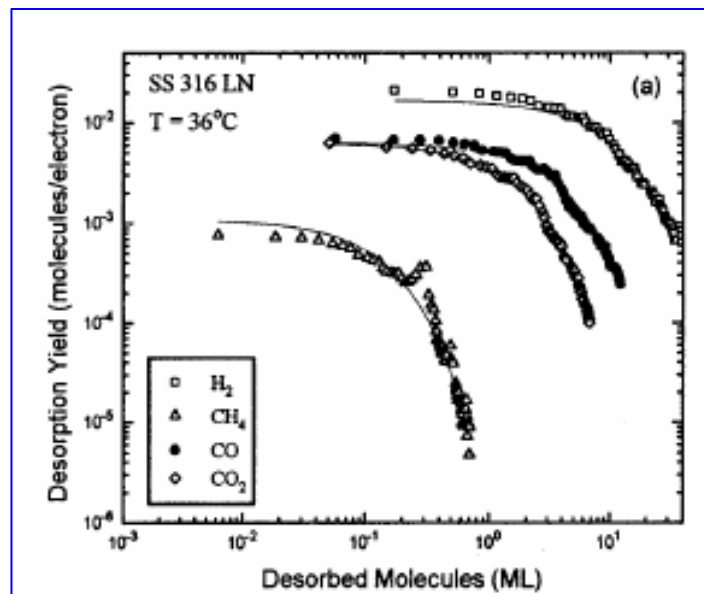


Fig. 3-b: Electron desorption yields for stainless steel for 300 eV electrons as a function of the integrated desorbed molecules measured in mono-layers equivalent ($1 \text{ ML} = 2 \times 10^{15} \text{ molecules cm}^{-2}$)

To carry out the calculation the following values are considered:

Gas	η_0 [molec per e ⁻]
H ₂	$2.5 \cdot 10^{-2}$
CH ₄	$1 \cdot 10^{-3}$
CO+CO	$2 \cdot 10^{-2}$

At the beginning of the bombardment the degassing rate q_0 is given by eq. 2:

$$q_0 = \frac{I}{e} \eta_0 k_B T \quad [\text{Eq. 2}]$$

Where I is the current of the impinging electrons, 'e' the electron charge and $\frac{1}{k_B T} \left[\frac{\text{molecules}}{\text{Torr} \cdot \ell} \right] = \frac{1}{1.03 \cdot 10^{-22} \cdot (273 + 150)} = 2.3 \cdot 10^{19}$ converts quantity of molecules in Torr l.

$$\text{For H}_2: q_0 = \frac{0.1}{1.6 \cdot 10^{-19}} \frac{0.025}{2.3 \cdot 10^{19}} = 6.8 \cdot 10^{-4} \text{ Torr l s}^{-1}$$

The evaluation of the dose is not trivial; actually, the electron bombardment is presumably not uniform and the bombardment area is not well defined. In the worst condition (slowest beam induced cleaning) the bombardment is uniform on the whole surface and on both sides of the electrodes (electrons coming in and out):

$$D \left[\frac{\text{C}}{\text{cm}^2} \right] = \frac{I \cdot t}{A}$$

Always in the same frame of worst scenario, the value of α that will be used in the calculation is the lowest of those reported, i.e. 0.6.

Taking into account the variation of η with the dose D [C cm⁻²], for H₂:

$$\eta_{H_2} = \eta_0 = 2.5 \cdot 10^{-2} \quad \text{for } D < 10^{-1} \text{ C cm}^{-2} \quad \text{that is for working time less than 7600 s,}$$

$$\eta_{H_2} = (\eta_0 D_0^\alpha) \cdot D^{-\alpha} = \frac{(2.5 \cdot 10^{-2} \cdot 0.1^{0.6})}{D^{0.6}} = \frac{6.3 \cdot 10^{-3}}{D^{0.6}} = \frac{A^{0.6} \cdot 6.3 \cdot 10^{-3}}{I^{0.6} \cdot t^{0.6}} = \frac{5.3}{t^{0.6}} \quad \text{for } t > 7600 \text{ s} \quad [\text{Eq. 3}]$$

and for the outgassing rates:

$$q_{H_2} = q_0 = 6.8 \cdot 10^{-4} \left[\frac{\text{Torr} \ell}{\text{s}} \right] \quad \text{for } t < 2 \text{ h}$$

$$q_{H_2} = \frac{0.1}{1.6 \cdot 10^{-19}} \frac{5.3}{t^{0.6}} \frac{1}{2.3 \cdot 10^{19}} = \frac{0.14}{t^{0.6}} \left[\frac{\text{Torr} \ell}{\text{s}} \right] \quad \text{for } t > 2 \text{ h} \quad [\text{Eq. 4}]$$

The results are reported in tab. 2 after different times of operation.

Time	D [C cm ⁻²]	η_{H_2} [m/elec.]	η_{CH_4} [m/elec.]	η_{CO+CO_2} [m/elec.]	q_{H_2} [Torr l s ⁻¹]	q_{CH_4} [Torr l s ⁻¹]	q_{CO+CO_2} [Torr l s ⁻¹]
1 day	1.2	5.79×10^{-3}	2.31×10^{-4}	4.63×10^{-3}	1.53×10^{-4}	6.11×10^{-6}	1.22×10^{-4}
1 month	34.4	7.52×10^{-4}	3.01×10^{-5}	6.01×10^{-4}	1.99×10^{-5}	7.94×10^{-7}	1.59×10^{-5}
1 year	419	1.68×10^{-4}	6.72×10^{-6}	1.34×10^{-4}	4.44×10^{-6}	1.78×10^{-7}	3.55×10^{-6}
10 years	4190	4.22×10^{-5}	1.69×10^{-6}	3.38×10^{-5}	1.11×10^{-6}	4.46×10^{-8}	8.92×10^{-7}

Table 2: desorption and degassing rates for increasing doses

The total quantity of gas desorbed (in Torr l) can be evaluated integrating eq. 4:

$$Q_{H_2} = 6.8 \cdot 10^{-4} \cdot 7600 + \int_{7600s}^{10y} \frac{0.14}{t^{0.6}} dt = 5.2 + 0.35 \cdot \left[(3.1 \cdot 10^8)^{0.4} - (7600)^{0.4} \right] = 864$$

$$Q_{CO+CO_2} = 690$$

$$Q_{CH_4} = 34.6$$

It is worthwhile to note that these quantities depend strongly on the choice of the bombarded surface and on the α coefficient. The surface of bombardment could be 80 times lower than that considered for the calculation and therefore also the quantity of desorbed gas if the electron impacts are limited on a 1 cm circle surface; in addition, without modifying the surface area, by choosing $\alpha=1$, instead of 0.6, the total hydrogen load is reduced by a factor of 14.5.

A better approach would be to estimate the total quantity of gas available on the electrodes surface and to consider this value as the upper limit for the total gas load.

For H₂ this amount is already counted in the static outgassing contribution (experimental results recently obtained in the TS-MME-SC laboratory show that in pure Ti sheets, after vacuum firing, the quantity of H₂ is less than 1 wt. ppm).

For CO and CO₂ it is supposed that their total load equals that of the oxygen atoms in the oxide layer. For a 10 nm thick oxide layer (quite pessimistic), namely about 40 ML (2×10^{15} molec cm⁻²) such value is about 26 Torr l.

2.3 Summary of the quantities taken into account for the design of the vacuum system.

	Dynamic	
	max q Torr l s ⁻¹	gas load Torr l
H ₂	6.8×10^{-4}	≈ 400
CH ₄	2.7×10^{-5}	(*)
CO+CO ₂	5.4×10^{-4}	≈ 26

(*) Not relevant for the design of NEG pumps

Tab. 3 Summary of the maximum degassing rate and of the total gas load

The minimum pumping speed needed to maintain the total pressure lower than 10⁻⁴ Torr during the totality of the working time is about 7 ls⁻¹, 6 ls⁻¹ and 0.3 ls⁻¹ respectively for H₂, CO+CO₂ and CH₄.

3. PROPERTIES OF THE CHOSEN NEG MATERIAL

Between the NEG materials that can be activated at low temperature, St707 is the most widely used in vacuum technology [5]. Powders of this getter are deposited and fixed on both side of a constantan strip. The thickness of the St707 getter layer is usually 70 μm which corresponds to a quantity of getter powder of about 10 g/m for each side of the strip (20 g/m considering both sides).

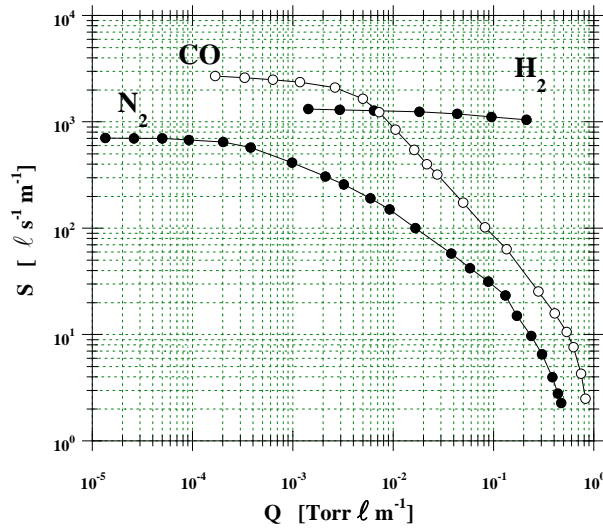


Fig. 4: Pumping speed of a fully activated St707 strip for H₂, CO and N₂ as a function of the respective quantity of gas adsorbed

St707, as for all other getter alloys, pumps the common gases found in vacuum systems, except CH₄ and rare gases.

The pumping speeds of the fully activated strip are reported in Fig. 4 [1]. The most relevant characteristic for this study is the maximum gas capacity for CO and CO₂: about 0.8 Torr l m⁻¹ (meter of NEG strip). The pumping speed for these gases becomes less than 10 l s⁻¹ m⁻¹ after the adsorption of about 0.5 Torr l m⁻¹. The gas capacity can increase significantly when the NEG is maintained at high temperature because of the gas dissolution in the bulk.

Fig. 5 indicates the time needed to attain the maximum pumping speed for H₂ when heating at relatively low temperature: 300°C and 350°C.

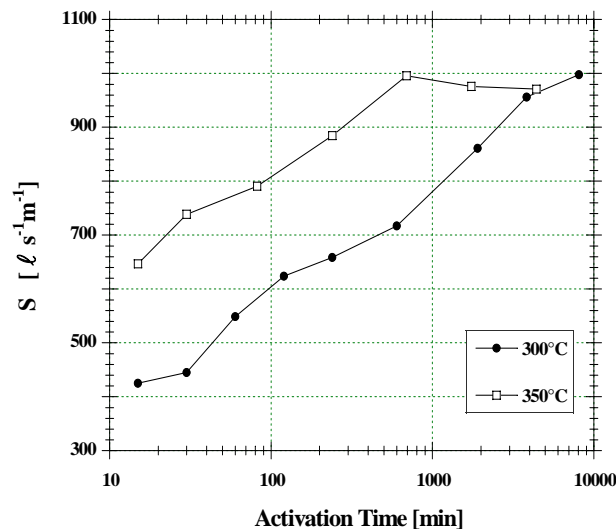


Fig. 5: Pumping speed for hydrogen H₂ as a function of the heating time at 300°C and 350°C

The hydrogen concentration in the NEG has to be lower than the embrittlement value, which is about 10 Torr l g⁻¹. For concentration exceeding this limit the dissolved hydrogen can form hydride eventually leading to peel-off.

The hydrogen dissociation pressure for St707 as provided by SAES-Getters is:

$$\text{Log}(P) = 4.8 + 2 \cdot \text{Log}(Q_{H_2}) - \frac{6116}{T[K]}$$

where P is the H₂ pressure in Torr, Q_{H₂} is the hydrogen concentration within the alloy in Torr l g⁻¹ and T the temperature in K.

4. PUMPING OF THE CNGS MONITOR BY ST707 STRIPS UNIQUELY

To assure the vacuum requirement in the 10 years of working, the NEG pump has to absorb about 400 Torr l of H₂ in the bulk and adsorb about 26 Torr l of CO and CO₂.

The first constraint requires at least 40 g of NEG alloy, namely about 2 m of strip. H₂ dissociation pressure, even at the critical concentration of 10 Torr l g⁻¹, is always lower than 10⁻⁷ Torr at 150°C.

The second constraint is much more severe; assuming a saturation value of 0.5 Torr l m⁻¹, it comes out that 52 m of strip are necessary to pump the total gas load of CO and CO₂. It is essential to underline that the required length of the strip is directly correlated with the surface of electron impingement; the value given here is obtained for 7526 cm², namely the entire surface area of the electrodes (worst case).

The maximum required pumping speed to achieve pressures for H₂ and CO+CO₂ below 10⁻⁴ Torr is only few l s⁻¹ at the beginning of the electron bombardment, when the quantity of gas pumped by the NEG is very low. Therefore it seems that, whenever the total gas load requirements are fulfilled, pumping speed is not a crucial point.

In the sealed off monitor, pumped just by NEG materials, the pumping effect for CH₄ is due to the ionization of the molecules by the 300 eV energy secondary electrons.

The ionization pumping speed can be evaluated when the ionization cross section σ is known. The value considered, namely 3x10⁻²⁰ m², is taken from Fig. 6 [6, 7].

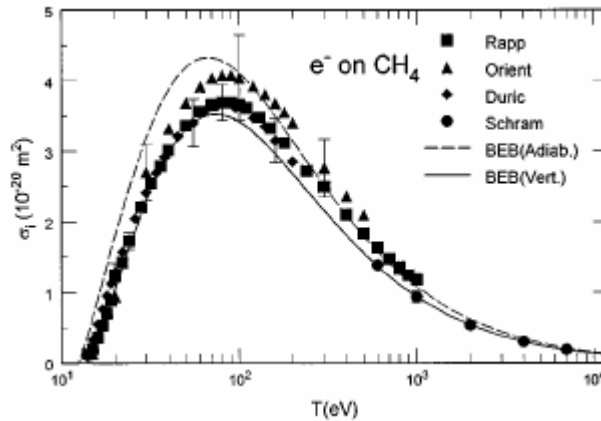


Fig. 6: Methane ionization cross section as a function of the electron kinetic energy [6]

The ionization rate ρ in the volume V, due to the electron current I, is: $\rho_{CH_4} = \frac{I}{e} \cdot \frac{\sigma}{A} (n \cdot V)$

where n is the CH₄ density and A the surface of bombardment; if d is the distance between the electrodes (1 cm):

$$\rho_{CH_4} [s^{-1}] = \frac{I}{e} \cdot \sigma \cdot n \cdot d = \frac{I[A]}{e[C]} \cdot \sigma [m^2] \cdot d [m] \cdot \frac{P [Pa]}{k_b \left[\frac{Pa \cdot m^3}{K} \right] \cdot T [K]}$$

In traditional vacuum technology units:

$$\rho_{CH_4} \left[\frac{\text{Torr} \cdot \ell}{s^{-1}} \right] = \frac{I}{e} \cdot \sigma \cdot n \cdot d = \left(\frac{I[A]}{e[C]} \cdot \sigma[m^2] \cdot d[m] \cdot \frac{P[Pa]}{k_b \left[\frac{Pa \cdot m^3}{K} \right] \cdot T[K]} \right) \cdot k_b \left[\frac{\text{Torr} \cdot \ell}{K} \right] \cdot T[K]$$

For the pumping speed S_{CH_4} :

$$\begin{aligned} S_{CH_4} \left[\frac{\ell}{s^{-1}} \right] &= \frac{\rho_{CH_4} \left[\frac{\text{Torr} \cdot \ell}{s^{-1}} \right]}{P[\text{Torr}]} = \left(\frac{I[A]}{e[C]} \cdot \sigma[m^2] \cdot d[m] \cdot \frac{P[Pa]}{k_b \left[\frac{Pa \cdot m^3}{K} \right] \cdot T[K]} \right) \cdot \frac{k_b \left[\frac{\text{Torr} \cdot \ell}{K} \right] \cdot T[K]}{P[\text{Torr}]} = \\ &= \left(\frac{I[A]}{e[C]} \cdot \sigma[m^2] \cdot d[m] \right) \cdot \frac{P[Pa]}{P[\text{Torr}]} \cdot \frac{k_b \left[\frac{\text{Torr} \cdot \ell}{K} \right]}{k_b \left[\frac{Pa \cdot m^3}{K} \right]} = \left(\frac{I[A]}{e[C]} \cdot \sigma[m^2] \cdot d[m] \right) \cdot 133 \cdot 7.52 = \\ &= 10^3 \cdot \left(\frac{I[A]}{e[C]} \cdot \sigma[m^2] \cdot d[m] \right) = 0.19 \left[\frac{\ell}{s^{-1}} \right] \end{aligned}$$

This calculated value is just enough to keep the CH_4 pressure below 10^{-4} Torr after one day of working.

5. PROPOSED SOLUTION: COUPLING OF ION AND NEG PUMPING

The calculation shows that at the beginning of the operation the CH_4 pressure is rather close to the critical value whether its pumping is ensured exclusively by the electron ionization; in addition, massive electron pumping of methane could led to a faster variation of the secondary electron yield induced by a graphitic carbon layer built-up on the electrode surface.

Therefore, it seems reasonable to couple the NEG pumping with ion pumping at least at the beginning of the operation (see Fig. 7).

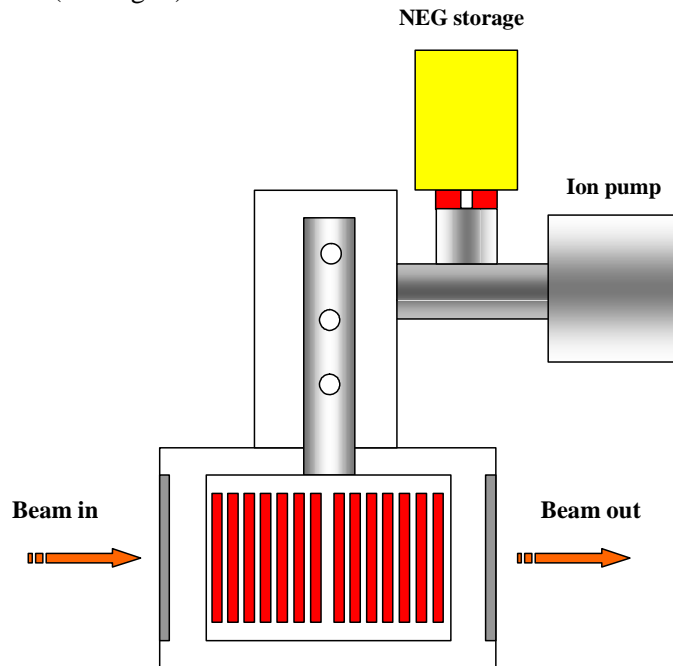


Fig. 7: The proposed pumping solution, ion pumping is necessary during the first year of operation only

The addition of an ion pump could offer many advantages in the first year of operation:

- the pressure of methane would be for all time at least two orders of magnitude below the required limit.
- it would pump most of the methane, i.e. 100 times more than the electrons for an effective pumping speed in the electrodes zone of 20 ls^{-1} , hence slowing down the surface conditioning.
- it would adsorb part of the $\text{CO}+\text{CO}_2$ desorbed during the first year of operation (at least one half of the total quantity)

This last point allows reducing the total quantity of NEG strip if a small aperture separates the vessel where the strip is inserted from the rest of the system. For example, for an aperture giving a conductance of 5 ls^{-1} and an ion pump providing an effective pumping speed of 30 ls^{-1} , the length of strip can be reduced to 30 m in the worst scenario (uniform bombardment over the entire electrodes surface). This quantity can be easily packed inside a 10 cm diameter, 30 cm long stainless steel vacuum chamber.

After the first year of operation the ion pump is no longer necessary because of the reduction of the desorption yields. In the worst scenario, the outgassing rates at that time will be 4.4×10^{-6} and $3.5 \times 10^{-6} \text{ Torr l s}^{-1}$ for H_2 and $\text{CO}+\text{CO}_2$ respectively and, hence, 5 ls^{-1} are largely enough to fulfill the requirements. For methane the outgassing rate will be $1.8 \times 10^{-7} \text{ Torr l s}^{-1}$ and the beam induced pumping should lead to a pressure in the 10^{-6} Torr range.

This implies that the ion pump will be effectively used for the first year only and that, after this time, its repairing shall not be indispensable in case of failure.

6. RECOMMENDED PRELIMINARY TREATMENTS

The calculations reported are based on the assumption that the preconditioning of all materials and the design are suitable for UHV applications. In addition, vacuum firing of all the metallic components and air firing of ceramics are strongly recommended, in particular for the Ti electrodes.

Bakeout temperatures higher than 300°C provide a partial dissolution of the oxide layer of the Ti electrodes, which reduces the desorption yields by at least one order of magnitude and the secondary electron yield down to about 1.3 at the peak.

FINAL REMARK: this note does not take into account the heating of the electrodes due to the beam crossing.

ACKNOWLEDGMENTS

F. Zimmermann and P. Costa Pinto provided me reference 6 and 7 respectively.

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