



Frascati, July 8, 1991

Note: **V-3****PRELIMINARY STUDY FOR THE CHOICE OF THE DAΦNE VACUUM CHAMBER MATERIAL**

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The design value of the dynamic pressure in DAΦNE is 10^{-9} mbar dictated by the need to keep the gas background at a reasonable level rather than by lifetime requirements. This value of the pressure is quite an ambitious goal and the choice of the material for the vacuum chamber is a very important step. In order to select the most suitable material for the DAΦNE vacuum chamber theoretical and experimental results on some aluminum alloys and stainless steel are reviewed. Copper won't be considered at this step because of its high residual radioactivity and mechanical properties, quite worse compared to the stainless steel ones.

The use of aluminum vacuum chambers for high energy accelerators like SPEAR, PETRA, PEP, DCI, CESR, SRS, NSLS, Photon Factory etc. [1] has provided an intense comparative study on stainless steel and aluminum performances.

Many parameters are to be considered such as electrical and thermal conductivity, outgassing rate and its sensitivity to surface treatments, residual radioactivity and the ability of producing the required shape for the vacuum chamber.

Some properties of Aluminum 6061T6 and Stainless steel 304 LN [2] are reported in Table 1. We can see that, as well as thermal and electrical conductivity, residual radioactivity, magnetic and mechanical characteristics are considered aluminum and aluminum alloys are preferable materials for ultrahigh vacuum systems of large electron storage rings.

The total gas load of a vacuum system [3] is the sum of the residual gas remaining from the initial atmosphere, the vapour pressure of the materials present in the chamber and the leakage, outgassing and permeation. The first two terms can limit the ultimate pressure of the system if the precautions required for the high vacuum are not respected. Usual high and ultrahigh vacuum systems have their ultimate pressure determined by leakage, outgassing and permeation.

$$P_u = \frac{Q_G}{S} = \frac{Q_L + Q_D + Q_P}{S} \quad (1)$$

where Q_G is the total gas load, Q_L is the component due to the leakage, Q_D to the outgassing, Q_P to the permeation and S is the pumping speed in the chamber.

Table 1 - Properties of commercial grade aluminum alloy and stainless steel [2]

	Aluminum	Stainless
Commercial grade	6061T6	304 LN
Chemical Composition (weight)	Al >96 % Si 0.4÷.8 Fe 0.7 Cu 0.15÷0.40 Mn 0.15 Mg 0.8÷1.2 Cr 0.15÷0.35 Zn 0.25 Ti 0.15	Fe >64.5 % Cr 18÷20 Ni 8÷12 Mn <2 Si <1 C <0.03 N 0.2÷0.4 S <0.03 P <0.045
Condition	Hard	Annealed
Specific Gravity	2.7	7.8
Modulus of Elasticity (psi)	1×10^6	28×10^6
Modulus of Rigidity (psi)	3.75×10^6	10.5×10^6
Thermal expansion coefficient ($^{\circ}\text{C}^{-1}$)	23×10^{-6}	17.3×10^{-6}
Melting Point ($^{\circ}\text{C}$)	615	1410
Yield strength	40000	70000
Thermal Conductivity ($\text{cal s}^{-1} \text{cm}^{-1} \text{ } ^{\circ}\text{C}^{-1}$)	20 $^{\circ}\text{C}$ 4K 0.37 0.086	0.036 0.6×10^{-3}
Heat Capacity ($\text{cal g}^{-1} \text{ } ^{\circ}\text{C}^{-1}$)	20 $^{\circ}\text{C}$ 4K 0.21 62×10^{-6}	0.12
Electrical Resistivity (ohm m)	20 $^{\circ}\text{C}$ 4K 4.3×10^{-8} 1.4×10^{-8}	72×10^{-8} 50×10^{-8}
Bakeout Temperature ($^{\circ}\text{C}$)	150÷200	300
Secondary Electron Unit Yield Energy	50 eV	> 400 eV
Machinability	Excellent	Fair
Weldability	Good	Excellent
Magnetic Susceptibility ($\mu/\mu_0 - 1$)	2.1×10^{-8}	4×10^{-3}
Dominant Thermal Neutron Activation Cross Section, Isotope Produced and Half Life	0.21 mb Al 28 2.3 min	2.8 mb 15.6 mb 1.5 mb Fe 55 Cr 51 Ni 65 2.6 y 27.7 d 2.6 h

Limiting the discussion to the outgassing (namely the generation of gas resulting from the desorption) it's well known that the gas desorption in an electron storage ring is caused by thermal desorption and by the irradiation with the synchrotron radiation and several theoretical and experimental studies have been performed on both aluminum and stainless steel samples.

The gas load Q_D due to the outgassing is expressed by [3]

$$Q_D = q_D s \quad (2)$$

where q_D is the specific outgassing rate (e.g. Torr l s⁻¹ cm⁻²) and s is the area of the outgassing surface (cm²).

The mechanism of the outgassing from metal is quite complicated and several models have been proposed to explain the phenomenon.

Basically most of the models assume that the outgassing is an adsorption/desorption process, but this is true when the coverage is less than a monolayer. After the most accurate cleaning and etching procedure the oxide layer is quite thicker than a monolayer on both aluminum and stainless steel so another mechanism based on the *diffusion* of water vapor molecules out of the pores of the oxide layer, inevitably present on the surface of most metals [4], is then to be considered.

Chen et al. [5] studied the outgassing behaviour of A6063-EX aluminum alloy and SUS 304 stainless steel analyzing the outgassing rate curves and the residual gases in the vacuum system. Their results seem to indicate that in the case of aluminum is the diffusion of water vapor out of the porous oxide layer the major process which governs the outgassing behaviour when the sample surface has been exposed to moist gas. Instead, due to a different structure of the layer oxide, in the case of SUS 304 stainless steel it's a surface controlled desorption process. So the behaviour in presence of moist gas is quite different for the two materials, better for stainless steel and worse for aluminum. But when the chamber was filled with extremely dry N₂, after bakeout, the observed slopes of the outgassing rate were quite the same for the two materials. After the pumpdown the final values for the outgassing rate lied in the range of 1x10⁻¹³ and of 1x10⁻¹² Torr l s⁻¹ cm⁻² for aluminum and stainless steel respectively.

Halama and Herrera [6] measured, by two different methods, the thermal outgassing rates of the residual gases of long pipes of Al 6061 alloy. The residual gas in the pipe contained more than 99% H₂ with traces of CO and CO₂. Depending on different surface treatments (glow discharge in pure argon or oxygen) and bakeout temperatures (100, 150, 200 °C) of the samples they obtained for the thermal outgassing rate several values in the range of 10⁻¹³ Torr l s⁻¹ cm⁻². The lowest value of 1x10⁻¹⁴ Torr l s⁻¹ cm⁻², at room temperature, refers to a 200 °C bakeout for 24 h, and a glow discharge first with pure argon and then with pure oxygen. The most abundant residual gas in a baked-out Al system is H₂ which diffuses from the metal and this is in agreement with the fact that H₂ is the only gas known to be soluble in either solid or molten Al [7]. Other gases such as H₂O, CO, CO₂, and hydrocarbons seem to be adsorbed on the surface with a

continuous spectrum of binding energies and, after a 200 °C bakeout the binding energies of these gases are above the 25 kcal/mole and their outgassing rates are negligible at room temperature. During the oxygen glow discharge the oxygen combines with aluminum to form aluminum oxides, but also probably removes carbon from surface by forming CO and CO₂.

On the other side Odaka et al. [8] found that the outgassing rate of 316 L stainless steel is reduced by repeated baking/air exposure cycles and reaches a constant value 1×10^{-13} Torr l s⁻¹ cm⁻² after a few cycles. The air exposure appears to play a significant role in bringing the surface into the thoroughly degassed state. The lowest value found for stainless steel [3] lies in the range of 10^{-14} Torr l s⁻¹ cm⁻² after a bakeout at 300÷400 °C up to 100h.

In the electron storage rings, besides the thermal outgassing, the synchrotron radiation induced gas desorption from the vacuum chamber walls produces a large dynamic gas load. The quantum spectrum of synchrotron radiation is given by [9]

$$\begin{aligned} \frac{d^2N}{d\epsilon dt} &= \frac{9\sqrt{3}}{8\pi} \frac{W}{\epsilon_c^2 x} \int_x^\infty K_{5/3}(y) dy = \\ &= \frac{6.95 \times 10^{13}}{E^2} I \rho \int_x^\infty K_{5/3}(y) dy \text{ photons s}^{-1} \text{ eV}^{-1} \end{aligned} \quad (3)$$

where $x = \epsilon/\epsilon_c$, $\epsilon_c = 3/2hc(E/E_0)^3/\rho = 2.218 \times 10^3 E^3/\rho$ eV

$$W = \frac{4\pi}{3} \frac{r_e}{e} \frac{E^4}{E_0^3} \frac{I}{\rho} = 88.5 E^4 I/\rho \text{ Watts}$$

is the total radiated energy and

ϵ_c is the critical photon energy, which divides the power spectrum into two equal parts

E_0 is the electron rest energy

r_e is the classical electron radius

ϵ is the photon energy in eV

I is the beam current in mA

E is the machine energy in GeV

ρ is the bending radius in metres

The integral is taken over the modified Bessel function $K_{5/3}$.

The spectrum can be expressed in the following form

$$\frac{d^2N}{dxdt} = \frac{\sqrt{3}}{e\hbar c} EI \int_0^\infty K_{5/3}(y) dy \quad (4)$$

the number of photons contained in the spectral interval (0, x) follows by integration of the spectrum. Defining

$$F(x) = \int_0^x \int_0^\infty K_{5/3}(y) dy du \quad (5)$$

the photon flux can be expressed as

$$\dot{N}(x) = \frac{\sqrt{3r_e}}{e\hbar c} F(x) EI. \quad (6)$$

The function $F(x)$ has been computed and for $x \rightarrow \infty$ $F(x)$ takes the value 5.23.

With the numerical constants the total photon flux is

$$\dot{N} = 8.08 \times 10^{17} IE \text{ photons } s^{-1} \quad (7)$$

The gas load due to the photodesorption is

$$N_m = \eta_i \times \dot{N}(x) \text{ molecules } s^{-1} \quad (8)$$

where η_i [mol photon⁻¹] is the specific molecular desorption yield of the i th residual gas component.

From the studies of the synchrotron radiation induced gas desorption from vacuum chambers made of stainless steel and aluminum alloy [10, 11, 12] turns out that the mainly desorbed gas species are H₂, CH₄, CO and CO₂. Andritschky et al. [11] measured synchrotron radiation induced neutral gas desorption from samples of different vacuum chamber materials at the DCI storage ring at LURE, Orsay. Two alloys were selected, Aluminum type International Standard Organisation (ISO) AlMgSi (AA 6060) and a high temperature steel type 'Nimonic'. The critical energy spectrum ε_c of the photon spectrum was $\varepsilon_c = 773$ eV. The molecular desorption yield for the main desorbed gases has been derived from the flux of the desorbed gas Φ under photon bombardment. The initial desorption yields η at the first exposure of a sample are reported in Table 2.

The gradual desorption yield decreases during the continued exposure to photons, by the so called process of "beam cleaning", as observed with synchrotron radiation in electron-positron storage ring, has been studied in more detail for hydrogen in aluminum.

The authors assumed that the desorbing hydrogen is first transported by a diffusion process to the surface and, neglecting chemical reactions on the surface (quite justified simplification in the case of hydrogen), that the gas-solid interaction may be characterized by both volume (diffusion) and surface (adsorption, desorption) processes.

Table 2 Initial desorption yield η [mol/phot]

	AlMgSi	Nimonic
H ₂	1.9 x 10 ⁻³	1.2 x 10 ⁻³
CH ₄	5.7 x 10 ⁻⁴	2.2 x 10 ⁻⁴
CO	1.2 x 10 ⁻³	4.3 x 10 ⁻⁴
CO ₂	2.7 x 10 ⁻³	1.7 x 10 ⁻³

In a simple unidimensional model of diffusion the transport of molecules inside the bulk may be described by

$$\partial c/\partial t = -D\partial^2 c/\partial x^2 \quad (9)$$

and $\Phi = Kc$

where c [cm³ (STP*) cm⁻³] is the gas concentration inside the solid, K [cm s⁻¹] is a phenomenological constant depending on irradiation current, photon energy spectrum and cross section for desorption, D [cm² s⁻¹] is the diffusion coefficient in solids and Φ [cm³ (STP) s⁻¹ cm²] is the desorbed gas flux. Neglecting re-absorption phenomena because of high pumping speed and low absorption coefficient for hydrogen in aluminum, the net gas flux Φ leaving the surface is given by

$$\Phi = D\partial c/\partial x|_{x=0} = Kc|_{x=0} \quad (10)$$

Considering the surface as a semi-infinite plate with the boundary condition (11) and with a uniform concentration c_0 inside the bulk a solution of (10) is

$$\Phi = \Phi_0(t=0)[\exp((K^2/D)t)][1 - \operatorname{erf}(\{K^2/D\}t)^{-1/2}] \quad (11)$$

From this solution it follows that after an initial time t_0 Φ decreases as

$$\Phi \propto t^{-1/2}. \quad (12)$$

* Standard Temperature and Pressure: T=293 K, P=1 atm.

They found also that for Al samples the initial hydrogen concentration corresponds approximately to the hydrogen concentration in aluminum trihydroxide $\text{Al}(\text{OH})_3$, e.g. "Gibbsite", a product of the room temperature oxidation of aluminum. This is in good agreement with a model proposed by P. Marin [13] to explain the x-ray stimulated desorption of aluminum vacuum chamber. Besides the "natural" diffusion of H and O atoms in the bulk of the material also the breakdown of aluminum hydroxide molecules by photoelectrons is considered with the subsequent diffusion of H and O atoms to the surface and the formation of H_2 and O_2 molecules. Marin obtained for the net desorbed gas flux the same result of (13) and concludes that when the breaking of hydroxide molecules by photoelectrons is stopped the free hydrogen and oxygen atoms diffuse to the surface. In presence of irradiation the process continues with the $\text{Al}(\text{OH})_3$ concentration.

Andritschky et al. [12] applied their model to fit the obtained desorption yield values, (for H_2 , CH_4 , CO and CO_2 gases), as a function of the accumulated photon dose for different ISO aluminum alloy and 316 LN stainless steel vacuum chambers. The vacuum bakeout temperatures of the samples were 150 °C for aluminum and 300 °C for stainless steel. The synchrotron radiation induced initial gas desorption yield of stainless steel chambers was about 50÷150 times lower than for aluminum, partly as a consequence of the lower photoelectron production and partly of the smaller mean energy of photoelectrons for stainless steel. However after an accumulated dose of 10^{21} photons/m the photodesorption yields for the residual gases were slightly different for aluminum and stainless steel, namely in the range of 10^{-6} mol/ph for CH_4 , 10^{-5} for CO and CO_2 , and 10^{-3} for H_2 . (It may be argued that the different bakeout temperature of stainless steel would affect the gas desorption yield but in contradiction no lower value of η was found [10] with a 950 °C high temperature treatment of stainless steel). A similar behaviour to H_2 resulted for CO suggesting that the unidimensional diffusion model can be applicable also for CO. Further the surface roughness factor (e.g. the ratio between real and geometrical surface) was estimated as 2÷4 for Al and ~14 for stainless steel.

Conclusions

The theoretical and experimental results seem to indicate that, provided the appropriate cleaning procedure, the Aluminum alloys performances are quite comparable, sometimes even better, than the stainless steel ones, as far as the problems of thermal and photo-stimulated outgassing of the vacuum chamber walls are concerned. Anyway it has to be stressed that while the high temperature bakeout seems not to improve the stainless steel outgassing behaviour, (instead repeated cycles of baking and air exposure play an important role in reducing the stainless steel outgassing rate [8]), the *in situ* baking cycle at 150 °C seem to be unavoidable for aluminum alloys.

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