THE ANALYSIS AND CHOICE OF THE SYSTEM FOR ATTAINING VACUUM IN A 300 MeV ELECTRON STORAGE RING

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Conditions are considered for attaining a pressure of ~10^{-9} Torr in a vacuum chamber of the redesigned storage ring N100M with the use of both concentrated and distributed pumps. Estimates are made for admissible outgassing due to thermal desorption and synchrotron radiation-induced desorption; a variant of arranging the pumps along the perimeter of the N100M storage ring is proposed.

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1. INTRODUCTION

The currently available 160 MeV electron storage ring H100 can be used as a base to create a powerful source of γ-quanta, where the effect of Compton backscattering of a laser beam by relativistic electrons is used [1]. The existing infrastructure and equipment will provide a rise in the circulating beam energy of N100M (after redesign) up to 250…300 MeV. The common practice of attaining the required vacuum (~10^{-10} Torr) in high-energy (2...6 GeV) and lower-energy (up to 1 GeV) storage rings calls for the use of both concentrated and distributed pumps in view of intense gas flows stimulated mainly by synchrotron radiation (SR). Though the action of SR is less critical in low-energy facilities, the incorrect estimate of its effect can nevertheless impede the attainment of design parameters significantly [2].

2. THE CHOICE OF PUMPING SCHEME AND REQUIREMENTS ON GAS EVOLUTION VALUE

The storage ring N100M is to be operated with a circulating current of about 1 A in the energy range between 60 and 300 MeV.

To provide the electron beam lifetime of no less than 2 and 0.5 hours in the storage ring at injection energies of 250 and 60 MeV, respectively, the pressure P has to be about $5\cdot10^{-9}$ Torr. Irrespective of the nature of gas molecule desorption from the walls of the vacuum chamber, the pressure P in the chamber will be determined by the effective pumping speed S_{eff} and the total outgassing Q_0, the main constituents of the latter being the thermal desorption Q_t and the stimulated desorption Q_γ:

$$P = \frac{Q_o}{S_э} + P_{\lim} = \frac{Q_t + Q_\gamma}{S_э} + P_{\lim}, \qquad (1)$$

where P_{lim} is the limiting pressure of pumps in the absence of outgassing.

To calculate the required S_{eff} at a given Q_0, we assume the vacuum chamber to be homogeneous along the whole perimeter of the storage ring, i.e., there are no elements of RF systems, diagnostics; there is no interaction between the electron beam and the laser beam, etc. The inner surface of the chamber has elliptical cross-section with semi-axes *axb* = *5x1.5* cm^2 at a length L_0 ~15 m, and has the area $S_s \approx 3.3$ m^2. The surface at bending sections makes only 21% of the total area, this being of importance in deciding on the pumping equipment with regard to desorption stimulated by synchrotron radiation. With storage rings as SR sources, it is common practice that more than 80% of the chamber length (e.g., for the LEP this is 83%) is subject to "cleaning" with the SR beam [3].

Let us consider the pumping system (Fig. 1) that comprises N pumps equally spaced over the length of the chamber, i.e., $L=L_0/N$, each pump having the pumping speed S_0.

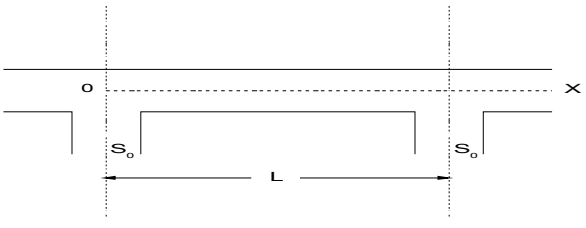

Fig. 1. *Scheme of pumping*

At molecular pumping conditions, the gas flow along the chamber is

$$Q(x) = -\omega \frac{dP}{dx}, \quad \frac{dQ}{dx} = Aq, \tag{2}$$

where $\omega = \frac{171 a^2 b^2}{\sqrt{a^2 + b^2}}$ is the specific molecular conductivity of the N100M chamber, being equal to 14.74 l·m/s for air; A is the specific area of the inner surface of the chamber, cm^2/m; q is the specific outgassing, Torr·l/(cm^2·s), whence we have

$$\omega \frac{d^2 P}{dx^2} = -Aq. \tag{3}$$

Using the boundary conditions dP/dx=0 at x=L/2 and P=AqL/S at x=0, we obtain from eq. (3) the following relations:

$$P(x) = Aq\left(\frac{Lx - x^2}{\omega} + \frac{L}{S_o}\right); \tag{4}$$

$$P_{\max} = Aq\left(\frac{L^2}{4\omega} + \frac{L}{S_o}\right); \tag{5}$$

$$P_{av} = Aq\left(\frac{L^2}{6\omega} + \frac{L}{S_o}\right) = \frac{ALq}{S_{eff}} = \frac{Aq}{nS_{eff}}; \tag{6}$$

$$S_{eff} = \frac{6\omega S_o}{S_o L + 6\omega}, \tag{7}$$

where for the N100M we have A≅2.202·10^3 cm^2/m; S_{eff} is the efficient pumping speed of one pump, l/s;

$$_nS_{eff} = LS_{eff}, \tag{8}$$

where $_nS_{eff}$ is the pumping efficiency per unit length, l/(s·m); C = ω/L is the chamber conductivity, l/s.

From expressions (4)-(8) it is seen that at L → 0 (distributed pumping) $S_{eff} = S_0$ and $\delta = S_{eff}/S_o \to 1$, and at L → ∞ we have $S_{eff} \to 0$ and δ → 0.

So, the choice of S_0 will mainly depend on various q, L values. The decisive factor here will be the choice of the parameter:

$$\frac{P_{av}}{q} = \frac{AL}{S_{eff}} = AL\left(\frac{L}{6\omega} + \frac{1}{S_o}\right) \tag{9}$$

so that $P_{av} \le P_0$, i.e.,

$$\frac{P_o}{q} \ge AL\left(\frac{L}{6\omega} + \frac{1}{S_o}\right) \tag{10}$$

or

$$q \le \frac{P_o \cdot S_{eff}}{AL} \tag{11}$$

for the concentrated pumping, and

$$q \le \frac{P_o \cdot {}_nS_{eff}}{A} \tag{12}$$

for the distributed pumping. The value of specific outgassing due to all desorption processes will be deciding in the choice of S_0, L at given P_0.

Table 1 lists the values of q_0, S_{eff} and $\Sigma_n S_{eff} = {}_nS_{eff}\, L_0$ for the distributed pumping.

At present, it appears most judicious to use nonevaporable getters (NEG) for the distributed pumping [4]. For getter St707, the specific pumping speed is about 3 l/(s·cm^2). Table 1 gives the required NEG area values for the mentioned pumping speeds $\Sigma_n S_{eff}$. If the NEG strip width is chosen to be 2 cm, then at a two-sided deposition of getter on the strip, ~15 m in length, a pressure of 5·10^{-9} Torr will be provided at a specific outgassing less than ~3·10^{-9} Torr·l/(cm^2·s).

Table 1. *Parameters of distributed pumping for the required NEG with S_{NEG}=3 l/(cm^2·s), and two-side strip of width 2 cm*

q_0, Torr/(cm^2·s)	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}
$_nS_{eff}$, l/(s·m)	4040	440	44	4.4	0.44
Σ_nS_{eff}, l/s	66000	6600	661	66.1	6.6
Area, cm^2	22020	2202	220	22	2.2
Length, m	55.1	5.5	0.55	0.06	0.006

Let us now consider the requirement on q_{add} in the case of concentrated pumping.

Fig. 2 shows the functions $q_{add}=f(N)$ for different S_0 values at $P_0=P_{av}=5\cdot10^{-9}$ Torr. It is seen that with increase in the number of pumps and their pumping speed, the requirements for q_{add} tend to decrease, but even at S_0 = ∞ and N=15 (with interspace L = 1m, and this being impracticable) q_{add} must be no more than 2·10^{-10} Torr·l/(cm^2·s). Besides, an increase in S_0 over 150 l/s exerts no essential effect on the permissible q_{add} value. Fig. 3 and 4 show the functions $S_{eff}=f(S_0)$ and $\delta=S_{eff}/S_0=f(S_0)$ for different number of pumps. From the analysis of data in Fig. 2 to 4 it appears most reasonable for N100M to choose 8 sites of pumping with pumps having S_0 = 150 l/s. Their arrangement is shown in Fig. 6. The pressure distribution over the superperiod length is presented in Fig. 5.

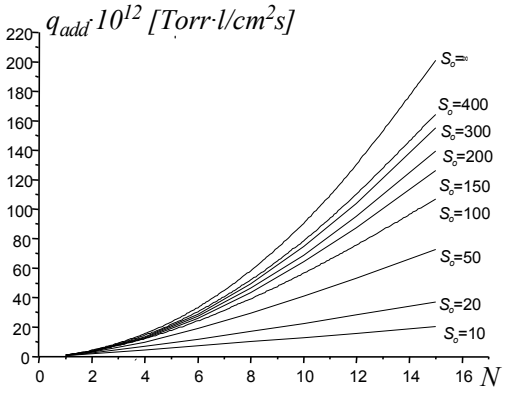

Fig. 2. *$q_{add} = f(N)$ for different S_0 values*

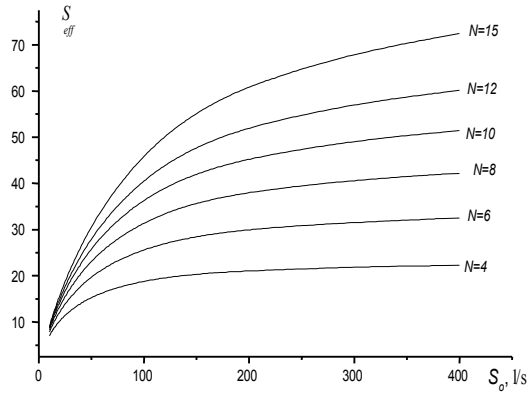

Fig. 3. *$S_{eff} = f(S_0)$ for different number of pumps*

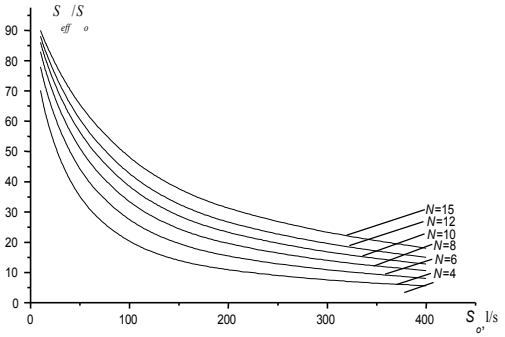

Fig. 4. *$\delta = S_{eff}/S_0 = f(S_0)$ for different number of pumps*

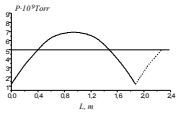

Fig. 5. *Pressure distribution over the length of superperiod*

The above-given requirements can be met with the pump Trion-150-HMTO-01-1 [5], which provides a limiting residual pressure of ~ 10^{-11} Torr with an increase in the start-up pressure up to ~$5 \cdot 10^{-2}$ Torr, evacuates noble gases and hydrocarbons. In the start of the pump a water cooling is used, while at ultimate vacuum conditions liquid nitrogen is used. Besides, at bending magnet sections, along with pumps 1, 4, 5 and 8, nonevaporable getters are provided for pumping. In this case, the process of manufacturing the chamber becomes more complicated in order to keep its electrodynamics smoothness. For N = 8, S_0 = 150 l/s, $P_0 = 5 \cdot 10^{-9}$ Torr we have $q_{add} = 4.35 \cdot 10^{-11}$ Torr·l/(cm^2·s). A further increase of demands for P_0 leads to a proportional decrease in q_{add}.

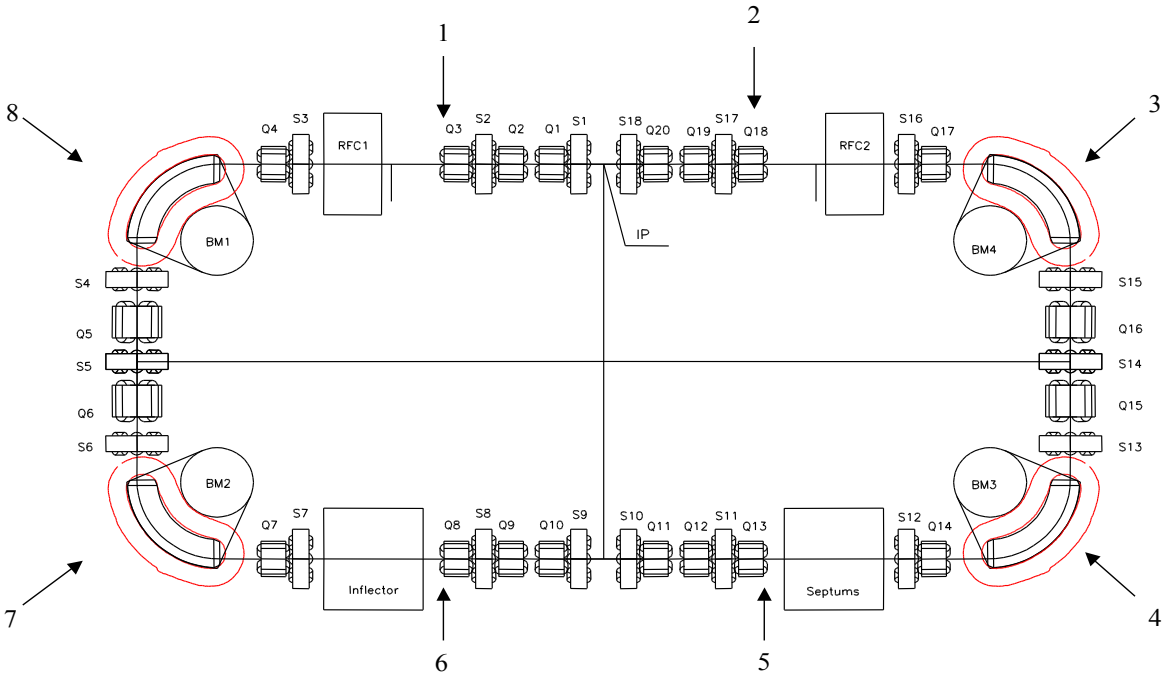

Fig. 6. *Layout of the facility H100M; the arrangement of pumps is shown by arrows.*

3. THE PROCESS OF VACUUM CHAMBER SURFACE TREATMENT

As mentioned above, of all the outgassing sources, thermal desorption and the desorption due to the SR effect (in the absence of leaks) are the main ones.

Of fundamental importance in the formation of desorption flows are the chemical composition and the structure of vacuum chamber material, the initial gas content in the chamber, the technological prehistory and the state of the surface. To reduce the flows, various technological techniques, methods and their combinations, realized during both the process of chamber manufacture and the periods of start-adjustment operations, long-term service, are used.

For N100M, stainless steel (SS) Kh18N10T appears the most suitable material.

For all storage-ring facilities, much attention is given to different methods of vacuum surface cleaning in order to reduce gas evolution. The description of these methods can be found in numerous publications; a short survey of the methods has been given in ref. [6]. Eventually, it has become possible to make chambers with $q_T \sim 10^{-13}$ l·Torr/(cm^2·s). However, in this case, expensive methods of chemical, physical and special cleaning (including the SR-beam or glow-discharge cleaning) are used.

For our purposes, the most low-cost methods of attaining vacuum-clean surfaces must be chosen. In any case, to initiate start-adjustment operations, q_T must not exceed 10^{-10} l·Torr/(cm^2·s). So, for our conditions and possibilities, the NIIEFA experience [7] appears the most acceptable. According to this experience, the untreated stainless steel has $q_T \cong 3 \ldots 8 \cdot 10^{-7}$ l·Torr/(cm^2·s), and after turning followed by washing in gasohol $q_T = 10^{-9} \ldots 5 \cdot 10^{-10}$ l·Torr/(cm^2·s). A subsequent continuous pumping (no less than 100 hours), a moderate warming-up (no higher than 150°C), the use of glow discharge provides a more than two-order improvement in the q value. And the following cleaning with the SR makes q still better. Though here there are some questions arising from the comparison with other storage rings, including the SR sources. First, since the SR flow $\dot{N}_\gamma \approx EI, \varepsilon_c \approx E^3$, and the injection energy in the N100M is assumed to be 60 MeV, then the SR "cleaning" without a rise in the stacked beam energy would be little efficient. At E = 60 MeV, there will be very little photons having an energy higher than 5 … 10 eV, starting with which the process of gas molecule desorption is most probable. Therefore, as early as at the injection stage we must have vacuum no worse than $5 \cdot 10^{-9}$ Torr before the necessary lifetime (~0.5 h) can be provided. Therefore, it is desirable that the chamber should be moderately warmed-up (up to 150°C) and could be cleaned with a glow discharge. Secondly, as mentioned above, the SR cleaning in the N100M is possible only for ~20% of the chamber surface (at bending sections), therefore 80% of the chamber should be cleaned with a glow discharge, this being most efficient with simultaneous warming-up of the chamber. Besides, considering that the binding energy of water is higher than that of gases (H_2, CO, CO_2, CH_4, etc.), the removal of water also calls for warming-up. The vacuum surface can efficiently be cleaned with a glow discharge in a gas mixture. Ar + O_2 (10%) is the mixture most widely used for glow-discharge cleaning. However, the presence of Ar after the cleaning is completed may have a significant effect on the beam life (inversely proportional to z^2). The removal of Ar is favored by the chamber warm-up and by the use of trions. So, it appears more preferable to use the helium-oxygen (10%) mixture for the glow discharge [6].

In the general case, the gas flow from the vacuum chamber walls is determined by the desorption from the surface, by diffusion from the bulk of the material and by the wall permeability. The kinetics of heat evolution of gas physically adsorbed by the surface in vacuum is described by the function close to t^{-1} for unbaked metal materials. The process of attaining the required vacuum, during which the desorption of physically adsorbed gases (vapors of water, nitrogen; carbon and hydrocarbon oxides; oxygen) is dominant, lasts for 10^5 to 10^6 s (28 to 277 hours). At the next stage of pumping, it is the diffusion flow from the bulk of materials (mainly, hydrogen) that becomes dominant, it is described by the kinetic dependence of type $t^{-0.5}$. The duration of this stage is estimated to be $10^6 < t < 10^7$ s (277-2770 hours). Later on, the gas flow due to wall permeability, having a constant value, becomes dominant. It is obvious that at these conditions the role of chemical and thermal methods of cleaning reduces to: (i) a decrease in the quantity of physically adsorbed gas, (ii) acceleration of desorption processes, and (iii) the formation of an oxide layer on the surface; this layer has a very low permeability and thus "blocks" hydrogen dissolved in the metal. All the mentioned cleaning methods (chemical, thermal, radiation-stimulated) provide a significant decrease in gas flows for a shorter time and to lower values. For example, a one-hour warming-up in vacuum at 1000°C is equivalent (in q) to a 2500-hour warming-up at 300°C [8]. Therefore, in our case, the use of only a part of the methods developed for mechanical, chemical and thermal cleaning of surfaces cannot provide the required degree of vacuum chamber surface quality.

4. SYNCHROTRON RADIATION AND ITS EFFECT ON GAS DESORPTION

Below, we give the main relations that describe the SR characteristics.

The general losses by the SR are given by

$$P_\gamma = 88.6 \frac{E^4 I}{\rho}; \text{ [GeV], [mA], [wt], [m]} \qquad (13)$$

The critical energy of the photon is

$$\varepsilon_c = 2.22 \cdot 10^3 \frac{E^3}{\rho}; \text{ [eV], [GeV], [m]} \qquad (14)$$

The total flux of photons of all energies is estimated as:

$$\dot{\Gamma} = 8.08 \cdot 10^{17} IE;) \text{ [l/s], [GeV], [mA]} \qquad (15)$$

The linear photon flux is calculated as

$$\frac{d\dot{\Gamma}}{dS} = 1.28 \cdot 10^{17} \frac{IE}{\rho}; \ [\text{l/(s·m)}] \qquad (16)$$

The gas flow due to the photon-induced desorption is given by $Q = \eta \dot{\Gamma}$, where η is the desorption coefficient [molecule/photon].

For the N100M, at I = 1 A we have $P_\gamma = 1.772 \cdot 10^5$ E[4], $\dot{\Gamma} = 8.08 \cdot 10^{20}$ E, $\varepsilon_c = 4.4 \cdot 10^3$ E[3]. Table 2 lists the values of these parameters.

The process of gas desorption by SR photons consists of two stages: under the action of photons secondary electrons are knocked out from the surface, these electrons then desorb the gases. It is assumed that the threshold photon energy is 10 eV, though some authors give it to be about 5 eV.

Table 2. *SR characteristics for the N100M at different energies*

E, GeV	0.05	0.06	0.07	0.1	0.15	0.2	0.25	0.3
ε_c, eV	$5.5 \cdot 10^{-4}$	0.95	1.51	4.4	14.85	35.2	68.75	118.8
P_γ, Wt	1.1075	2.3	4.25	17.72	89.71	283.52	692.19	1435.32
$\dot{\Gamma}$, 1/s	$4.04 \cdot 10^{19}$	$4.85 \cdot 10^{19}$	$5.66 \cdot 10^{19}$	$8.08 \cdot 10^{19}$	$1.21 \cdot 10^{20}$	$1.62 \cdot 10^{20}$	$2.02 \cdot 10^{20}$	$2.42 \cdot 10^{20}$

One liter of gas at a pressure of 1 Torr comprises $3.54 \cdot 10^{19}$ molecules/(l·Torr). Correspondingly, the flow of gas evolution under the SR action will be given by

$$Q_{SR} = \frac{\chi \dot{\Gamma} \eta}{3.54 \cdot 10^{19}} \frac{l \cdot Torr}{s}, \qquad (17)$$

where χ is the factor taking into account the number of photons having an energy higher than 5 to 10 eV.

This gas flow will mainly be concentrated at bending sections, where the chamber surface area equals 6918 cm^2, therefore the specific outgassing due to the SR will be

$$q_{SR} \approx 10^{-3} \eta \chi \frac{Torr \cdot l}{s \cdot cm^2}. \qquad (18)$$

Considering that this parameter should not be higher than 10^{-10} Torr·l/(cm^2·s), the η value should not be higher than 10^{-7}.

Numerous experimental data give

$$\eta = \eta_o \cdot D^{-\alpha}, \qquad (19)$$

where η_0 is the initial coefficient of desorption, η is the final desorption coefficient, D is the SR dose (in units mA h), α is the index equal to 0.6 … 1, depending on the information source.

Let us estimate the required time, for which $\eta \rightarrow 10^{-7}$.

From expression (19) it follows that

$$\lg\eta = \lg\eta_o - \alpha \lg D; \ \lg D = \frac{1}{\alpha} \lg\frac{\eta_o}{\eta}. \qquad (20)$$

For E=300 MeV and a stainless steel as a chamber material, we have $\eta_0 \sim 10^{-3}$ [9].

Then at $\alpha = 0.6$ we have $D_{0.6} = 10^6$ mA·h; at $\alpha = 1.0$ $D_{1.0} = 10^4$ mA·h. Or at I = 1000 mA, we have $t_{\alpha=0.6} = 816$ hours, $t_{\alpha=1.0} = 12$ hours.

In practice, the time of attaining the necessary vacuum conditions will be within the mentioned ranges.

5. CONCLUSION

At this stage of work on a preliminary choice of vacuum system design for the storage ring N100M it is evident that the attainment of necessary pressure ($5 \cdot 10^{-9}$ Torr) will mainly be determined by both the quality of the chamber material and the thoroughness of chemical, thermal and radiation-stimulated treatments of the chamber surface so that the initial specific gas evolution should be as minimum as possible at our conditions ($\sim 10^{-10}$ Torr·l/(cm^2·s)), and the pumping equipment should meet the above-mentioned requirements. At design stages to follow, it will be necessary to consider the arrangement of elements of different N100M systems in vacuum volumes, the principles of injection line structure.

REFERENCES

1. E. Bulyak, P. Gladkikh et.al. A compact X-ray source based on Compton scattering // *Nucl. Instr. and Meth. In Phys. Res. A*. № 467-468, 2001, p. 88-90.
2. H. Tongu, T. Shirai, et al. *Development of Evacuation System for Electron Storage Ring.* KSR. Proc. of EPAC 2000, Vienna, Austria, p. 2307-2309.
3. P. Strubin and Gröbner. *Vacuum system start-up and operation experience.* CERN/AT-VA/90-20.
4. C. Benvenutti *Molecular surface pumping: the getter pump.* CERN 99/05, p. 43-48.
5. *Vacuum Technique. Reference book*, M.: "Mashinostroyeniye", 1985, p. 282-284 (in Russian).
6. R.I. Reid. *Cleaning for vacuum service:* CERN 99/05, p. 139-153.
7. A.A. Glazunov, G.L. Saksagansky. *Vacuum of electrophysical facilities and complexes.* M.: "Energoizdat", 1985 (in Russian).
8. Karl Jousten. *Thermal outgassing:* CERN 99/05, p. 111-122.
9. C. Herbeaux, P. Marin et al. Photon-stimulated desorption of unbaked stainless-steel vacuum chambers // *Vacuum.* 2001, № 60, p. 113-122.