Vacuum pumping system for the multi-aperture low-energy continuously-operated electron accelerator with a high-density beam current

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Abstract. The vacuum pumping system for an electron accelerator has been developed on the basis of arc sources of getter film and ion getter pumps. The contradictory problem has been solved, that is, it was necessary to provide, on the one hand, the maximum efficiency of the pumping speed and, on the other, a minimal return flow of the metallic plasma shunting the accelerating gap. The program and procedure have been elaborated for the numerical simulation of getter pumping taking into account the mass-transfer non-uniformity. The experimentally obtained vacuum characteristics of the developed pumping system for the accelerator are presented.

1. Introduction

The multi-aperture low-energy electron accelerator (EA) under development at the JSC "NIIEFA' uses filament-type tungsten-thorium thermal cathodes as an electron emitter, with the beam extracted through the output foil window (OFW). The accelerator operates continuously with the following parameters of the electron beam: beam cross-section – 2000 cm^2, electron energy – 200 keV, beam current density behind the foil window – 100 μA/cm^2. To provide normal operation of the thermal cathodes and high-voltage gaps in the accelerator chamber the operating pressure should be maintained at a level of $1.3 \cdot 10^{-4}...6.7 \cdot 10^{-4}$ Pa (at the maximum allowable operating pressure of the thermal cathodes amounting to $2.6 \cdot 10^{-3}$ Pa).

The purpose of the study was to develop the vacuum pumping system (VPS) for an electron accelerator, with the VPS operating at widely varying temperatures and at extreme vibrations. Series-produced vacuum pumps (turbomolecular, cryosorption, diffusion oil-vapor pumps) are inoperable under such conditions. In these cases, high vacuum can be efficiently produced by arc sources (AS) of a getter film [1]. This pumping system is based on continuous or periodic deposition of a getter film (titanium) on the cooled surfaces and sorption of active gases by this film. Inert gases and hydrocarbons are pumped by an additional pump, as a rule, by an ion getter pump. These pumps have no moving parts and can operate under the above-mentioned environmental conditions. But, for normal operation the high-voltage gaps are to be protected against metal plasma flows generated by the arc sources (with an ionization degree of about 80 %), while providing the required pumping of gas release flows, including electron-stimulated gas release during extraction of a powerful electron beam through OFW. This paper presents the main results of calculations, design and tests of this vacuum pumping system.

2. Description of the vacuum pumping system

The vacuum chamber (CV) of the electron accelerator is made of stainless steel and has a volume of 0.35 m^3. The electron beam leaves through OFW located on the vacuum chamber wall. The thermal desorption flux in the electron accelerator chamber, including the electron-stimulated gas release, amounted, as calculated, to $1.2 \cdot 10^{-3}$ m^3Pa/s, but with the system of thermal cathode being switched-on and without beam extraction it amounted to $8.6 \cdot 10^{-4}$ m^3Pa/s. In the operation pressure range of the electron accelerator $(1.3–6.7)\cdot10^{-4}$ Pa the vacuum pumping system should provide the effective pumping speed of the chamber from 1.8 to 8.8 m^3/s. Such high pumping speed is ensured by the arc sources (AS1, AS2) of a getter film developed at the NIIEFA (figure 1), which is switched on immediately prior to generation of the electron beam. The vacuum arc sources do not pump out inert gases. In this connection, ion getter pumps (NM1, NM2) are used to maintain the background pressure and pumping of inert gases. Two ion getter NMD-0,4 pumps (with a pumping speed of 0.4 m^3/s each) ensure effective pumping speed of the electron accelerator chamber amounting to (0.4…0.5) m^3/s, which, as calculated, ensures a pressure of $(1.7…2.1)\cdot10^{-3}$Pa with thermal cathode glow in the electron accelerator chamber. The forevacuum system consists of the pump (NL1) NVR-16D, valve (VP1) and nitrogen trap (BS1) and is connected to the vacuum pumping system through the valve (VM1). Two wide-range vacuum gauges (PMT1, PMT2) serve for measurement of pressure.

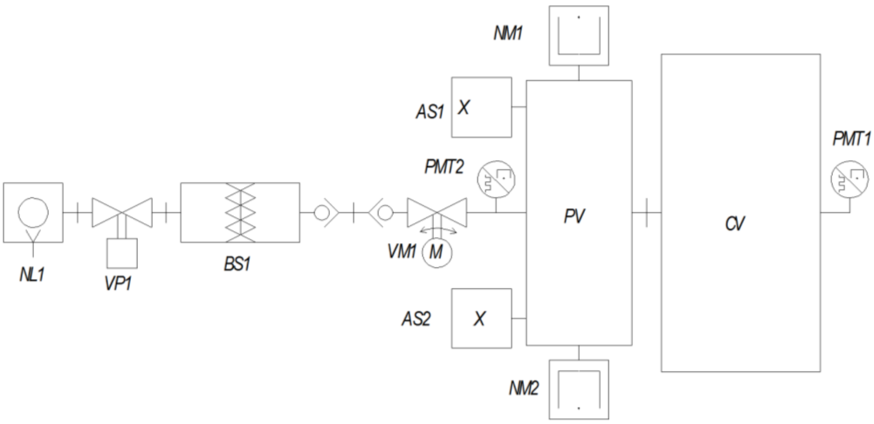


Figure 1. Basic diagram of the vacuum pumping system.

3. Analysis of design versions for the vacuum pumping system

To attain the optimal pumping parameters, to ensure reliability and serviceability several design versions of the vacuum pumping system of the electron accelerator were analyzed. The analysis was carried out both for continuous getter evaporation and for periodic mode. But, only the continuous operation mode of the arc sources turned out to be acceptable in all analyzed versions at the specified level of vacuum required for accelerator operation and at the calculated gas release fluxes.

The pumping speed S_{0ni} of the getter film as to i_{th} (nitrogen, oxygen, hydrogen) is defined by the sorbing surface area F_{cn}, m^2, and its specific pumping speed s_{0ni}, $m^3/(c\cdot m^2)$ [2, 3]:

$$S_{0ni} = s_{0ni} \cdot F_{cn} = 36.38 \cdot \beta_{0i} \cdot (T_i/M_i)^{0,5} \cdot F_{cn}, \quad (1)$$

where: $\beta_{0i} = 0.35$ – the initial coefficient of gas sticking to titanium (value for nitrogen) [2]; T_i = 293K – the gas temperature; M_i = 28 g/mole – the molar mass of gas (value for nitrogen).

At the film saturation degree less than the critical one ($Z_{cr} = 5 \cdot 10^{20}$ molecule/g, value for nitrogen on a titanium film) the sticking coefficient β_i is practically constant and amounts to the initial β_{0i}. With the saturation degree exceeding the critical value, the sticking coefficient is exponentially decreased. The basic values of Z_{cri} and β_{0i} for calculation of getter pumping are reported in [2–5], but they vary in a wide range. In this study, use was made of the refined numerical values of Z_{cri} *and* β_{0i} obtained experimentally [6].

The mass transfer non-uniformity of the getter and the evacuated gas can cause local changes in the sticking coefficient. To account for this, a program based on angular coefficient method was created in the Octave GNU UNIX software. In this case, the titanium plasma was conventionally replaced by neutral particles with a sticking coefficient of titanium to the walls of the vacuum chamber α=1. All surfaces with a getter film are divided on the surface, within which the distribution of the getter will be considered homogeneous. The program calculates the incident and pumped out fluxes of the getter and gas, the sticking coefficients of the selected surfaces according to a given inlet gas flow. First, according to the cosine law of reflection, the mass transfer coefficients (probability of a particle from one surface site to another) between the selected surfaces are calculated. The fluxes of the getter are calculated on the selected surfaces at a known rate of evaporation of the getter (2…5 mg/s).

The gas incident flux on the i-th surface and its sticking coefficient are determined from:

$$G_i = \sum_{j=1}^{n} W_{ji} = \sum_{j=1}^{n} (w_{ji} + G_j \cdot \varphi_{ji} \cdot (1 - b_j)) \quad (2)$$

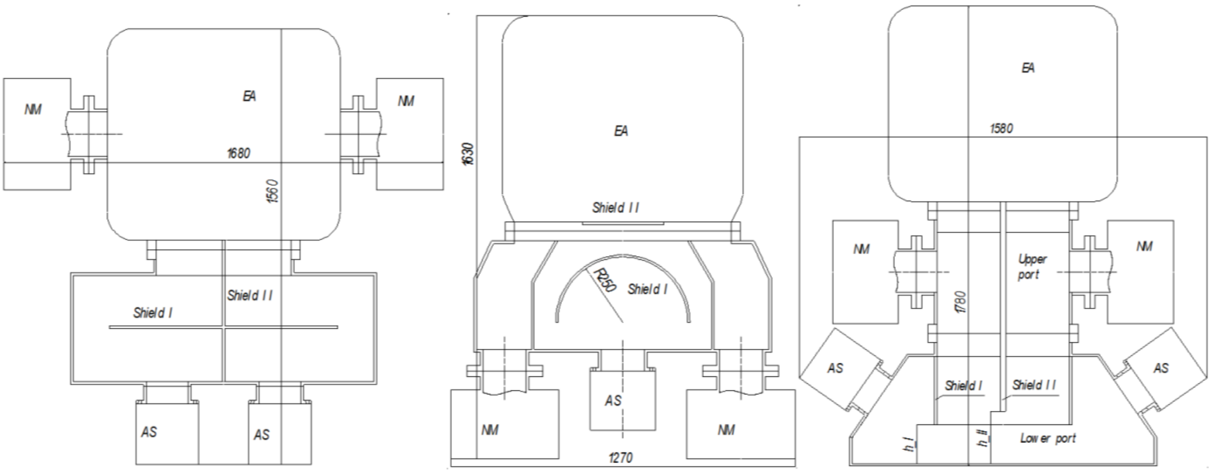
$$b_i = f_{app}(Z_i) = f_{app}\left(Q_i / \overline{m_{geti}}\right) = f_{app}(b_i \cdot G_i) \quad (3)$$

where W_{ji} –outgoing flux from j-th surface to i-th surface, m^{3}Pa/s; $w_{ji} = w_j \cdot \varphi_{ji}$ – outgoing flux from j-th surface to i-th surface due to the intrinsic gas evolution of the surface ($w_j \neq 0$ only for gas inlet) j, m^{3}Pa/s; Q_i –the pumped out flux by i-th surface, m^{3}Pa/s; G_j – the total incident flux to j-th surface, m^{3}Pa/s; φ_{ji} – mass transfer coefficient from j-th surface to i-th surface; $f_{app}(Z_i)$ – function approximating the dependence of the sticking coefficient on the saturation degree of the getter; Z_i – saturation degree of getter on i-th surface, molecul/g; $b_{i,j}$ – sticking coefficient of i-th or j-th surface; $\overline{m_{geti}}$ – deposition rate of getter to i-th surface, g/s.

A system of $\boldsymbol{2 \cdot n}$, in the general case non-linear, equations is created for $\boldsymbol{n}$ selected surfaces by the equation (2, 3).The program solver realizes the solution of a system of nonlinear equations of the form F (x) = 0 in which: $\boldsymbol{n}$ unknown incident gas fluxes G_i and $\boldsymbol{n}$ unknown sticking coefficients $b_i$of surfaces.The total pumping speed is calculated for the averaged gas parameters based on the sticking coefficients obtained. This procedure makes it possible to significantly increase the accuracy of the calculation, especially with increased fluxes of evacuated gas or an unsuccessful design of inner surfaces resulting in a local oversaturation of the getter film.

The qualitative assessment of the return plasma flow into the electron accelerator chamber was performed with the sticking coefficient of titanium to the vacuum chamber walls equal to α = 0.99. This assessment has made it possible to compare the return plasma flows into the electron chamber for different design versions of the vacuum pumping system.

The analyzed design versions of the vacuum pumping system differ by arrangement of the ion getter pumps, arc sources, as well as by the design of the water-cooled inner shields I, II (figure 2).



(**a**) (**b**) one VAS not shown (**c**)

Figure 2. Design versions of the vacuum arc source.

The overall dimensions and serviceability of the accelerator determine the arrangement of the ion getter pumps and arc sources, as well as influence the conductivity of the vacuum pumping system pipeline. The water-cooled inner shields are intended to provide a sufficient area of the getter film and construction of a labyrinth, which protects the electron accelerator vacuum chamber with high-voltage

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electrodes against ingress of the metal plasma of getter material into the chamber, which might cause shunting of the high-voltage gap and a disruption in the normal operation regime of the electron accelerator.

With the NMD-0,4 pumps (NM) mounted on the electron accelerator (figure 2(a)), their stray magnetic fields might affect the accelerator operation. With the NMD-0,4 pumps or arc sources (AS) located vertically at the bottom (figure 2(a), (b)), generated dust and getter particles might cause shorting of their electrodes and make inoperative the vacuum pumping system.

The scheme in figure 2(c) provides ease of operation and the highest reliability of the vacuum pumping system. This design version contains two demountable water-cooled shields (shield I and shield II). With two shields being mounted, conductivity from the electron accelerator chamber to the volume with the getter film is minimal, but protection against the return plasma flow is maximal. With shield I removed and only shield II remained, the conductivity is markedly increased, but protection against the return plasma flow is reduced. As the numerical experiment revealed, while evaporation rate of the getter equal 4 mg/s, the particle flux into the accelerator chamber through the inlet flange amounted to $1.1 \cdot 10^{15}$ 1/s without the shield I (figure 2(c)) and to $1.0 \cdot 10^{14}$ 1/s with the shield I (h_I = 14 cm) (figure 2(c)). In both cases, conductivity of the pipeline to the chamber with sorbing surfaces ensures the required effective pumping speed. The final optimal design can be chosen only experimentally. The calculated characteristics of 4 versions of the vacuum pumping system are summarized in table 1.

Table 1. Main design characteristics of the vacuum pumping system

Parameter	Version *a*	Version *b*	Version c (h_I=14 cm)	Version *c* without shield I
Conductivity of 2 ASs, m^3/s	3.70	4.92	3.36	5.77
Getter area of 2 ASs, m^2	1.64	0.66	1.25	1.50
Pumping speed of 2 ASs for nitrogen, m^3/s	67.6	27.2	51.4	62
Effective pumping speed of 2 ASs, m^3/s	3.5	4.16	3.16	5.28
Conductivity of 2 NM pumps, m^3/s	1.88	1.48	1.62	1.62
Effective pumping speed of 2 NMs, m^3/s	0.56	0.52	0.54	0.54
Effective pumping speed of EA, m^3/s	4.06	4.68	3.70	5.82
Operation pressure of EA, 10^{-4} Pa	3.5	3.3	4.0	2.4

In the final design version chosen by the calculation results (figure 1(c)) the vacuum pumping system is mounted on the lower wall of the electron accelerator chamber and comprises two ports. Two NMD-0,4 ion getter pumps are symmetrically mounted on the upper port, and two arc sources are mounted on the lower "port-chamber". The inner water-cooled surfaces of the lower port with the installed shield are made as distributed pumping surfaces, which are dusted with getter. The demountable shields I are of different length in order to vary the size h_I from 14 to 40 cm, the demountable shield II is h_II = 15 cm in size. Figure 3 shows the calculated diagram of pressure in the electron accelerator chamber of the chosen design version.

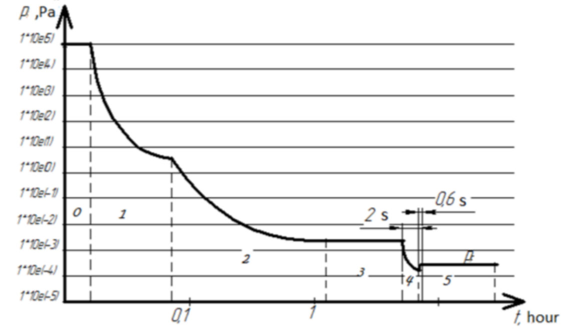

Figure 3. Time diagram of pressure in the EA chamber (without training regime): 0 – atmospheric pressure; 1 – forevacuum pumping; 2 – pumping of NM with a short-term start of AS; 3 – NM ensures background pressure; 4 – joint operation of AS and NM; 5 – extraction of electron beam through OFW.

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4. Testing of the vacuum pumping system

The vacuum pumping system was tested in the process of the adjustment and start-up of the electron accelerator. The background pressure (without generation of the electron beam) ensured by the ion getter pumps was maintained at the level of about $5 \cdot 10^{-4}$ Pa. Pressure during generation of the electron beam provided by the joint operation of the vacuum arc sources and ion getter pumps amounted to about $2 \cdot 10^{-3}$ Pa, which is higher than the calculated pressure. The reason might be that the training time of the electron accelerator with electron beam generation was not sufficient. Still, this pressure level provided the normal operation regimes of the high-voltage gap and thermal cathodes. With the inner shield I removed, the shunting current in the high-voltage gap of the electron accelerator prevented the electron beam with the required parameters from being obtained, while the shield, when being mounted (h_I = 14 cm), provided the normal operation of the electron accelerator. This design version of the electron accelerator was accepted as optimal.

5. Conclusion

The vacuum pumping system for the multi-aperture low-energy continuously-operated electron accelerator with a high-density beam current operating in the wide range of temperatures and extreme vibrations has been developed. This vacuum pumping system allows one to pump out high gas flows ensuring vacuum required for operation of the electron accelerator. The chosen scheme with the demountable shields makes it possible to adjust the system conductivity and distribution of getter fluxes to provide the normal operation of the accelerator.

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