3.8. Vacuum System

The operational efficiency of the synchrotron light sources is highly dependent on the design, construction and operational features of its vacuum system and highly defines the lifetime and the stable operation of the beam in the storage ring. The vacuum system of the accelerator is composed of three basic sub-systems: vacuum chamber, pumping system and the control system. The vacuum system has to comply with the following requirements:

- Vacuum chamber must utilize the inter-polar space of electromagnet to the fullest possible degree without distortion of the magnetic field in the gap.
- The vacuum chamber and the system must be capable of achieving and maintaining a vacuum better than 1 nTorr;
- The chamber material must be radiation-resistant and should provide small out gassing and penetrability.
- The vacuum chamber design should exclude the penetration of the working fluid vapors of the pumps.
- Construction and operation of vacuum system should be efficient and not be labour-intensive.

The vacuum system for the CANDLE storage ring has to provide the required vacuum pressure of about 1 nTorr in order to achieve an integrated beam lifetime of about 20 hours with a beam current in the range of 350 mA. To achieve these design goals the selection of the material for fabrication of the vacuum chamber is of great importance.

3.8.1 Vacuum Chamber Design

For intermediate energy light sources, stainless steel is a good choice for vacuum chamber material. Stainless steel material has excellent vacuum properties: low magnetic permeability $\mu \leq 1.005$, high density and good mechanical strength (longitudinal tension R=300 N/mm^2). Stainless steel can be well machined (manufactured) and be easily welded. Employment of stainless steel for efficiently manufacturing the vacuum chamber simplifies the technology and reduces costs.

The disadvantageous characteristics of stainless steel are its poor thermal conductivity and the relatively low electrical conductivity. To overcome the low thermal conductivity of the stainless steel vacuum chamber, copper is often used for photon absorbers. The low electrical conductivity leads to stronger resistive effects, especially in undulator vessels with very small apertures. Usage of a copper coat on the inner chamber surface solves this problem. On the other hand, the low electrical conductivity of the stainless steel results in low eddy current effects, which need to be taken into account when the global closed orbit correction system works at frequencies of 100Hz and higher [1].

The synchrotron radiation, that accompanies the circulating electron beam in the storage ring, stimulates desorption of molecules from those areas of vacuum chamber on which radiation impinges. The two types of observed desorptions are: thermal desorption and photo-desorption. Thermal desorption is caused by heating of chamber walls during partial absorption of synchrotron radiation by chamber material. The photo-desorption is driven by synchrotron radiation and is a two-step process: primary photons have a small cross-section for molecule desorption, but kick out photoelectrons from the surface with larger cross-section than for desorption. The kicked-out electrons under the influence of synchrotron radiation magnetic field return to the chamber wall. Both desorption mechanisms lead to a chamber pressure, which increases proportionally to the beam current. Four main types of molecules released from the walls: CO_2, CO, CH_4 and H_2 [1]. In order to attain high vacuum in third generation storage ring chamber and to minimize the impacts of the desorption process, the vacuum chamber design is based on the antechamber concept: the chamber is composed of two parts for maintaining the stored electron beam and for handling the synchrotron radiation [2]. The features of this solution are described below.

In CANDLE, the main vacuum chamber of the storage ring consists of 16 identical sectors (number of magnetic lattice periods), which are connected by bellows junctions [3]. Each sector is divided into 4 sections that correspond to two dipole sections (dipole 1, dipole 3), focusing section (2) and straight section (4) of vacuum chamber. The sections are connected by conflate flanges with smooth contact surfaces. In order for the chamber to have small impedance, the electron channel has the same section in the region of the electron beam trajectory.

The main parameters of the vacuum chamber are presented in Table 3.8.1

Table 3.8.1 Main parameters of the vacuum chamber.

Vacuum [nTorr]	1
Material	Stainless steel 12X18H10T ГОСТ 5632-72
Thickness of the sheet [mm]	3
Inner dimensions of electron channel [mm]	30 x 74
Gap [mm]	12
Minimal width [mm]	150
Maximal width [mm]	320
Maximal length of one section [mm]	4708

The general view of the vacuum chamber together with the magnetic elements for one standard period and the photon beam line ports is shown on Figure 3.8.1. Each section has a pumping port. The sections that serve the extracted photon beam lines and where the synchrotron radiation is basically observed, have the antechamber and the absorber stations.

The plan-view of the chamber geometry at different locations of the lattice is shown in Fig. 3.8.2. Sector 1 (length 3.506 m) can provide for an extraction of two photon beam lines: from the dipole BM01a and insertion device ID02, the sector 2 (length 2.004 m) can provide for one photon beam line from dipole magnet BM01b, keeping open the possibility for installing an insertion device and corresponding beam lines from wigglers or undulators in contiguous straight sector, sector 3 can provide one photon beam line from the dipole BM02a, sector 4 can provide one photon beam line from the dipole BM02b.

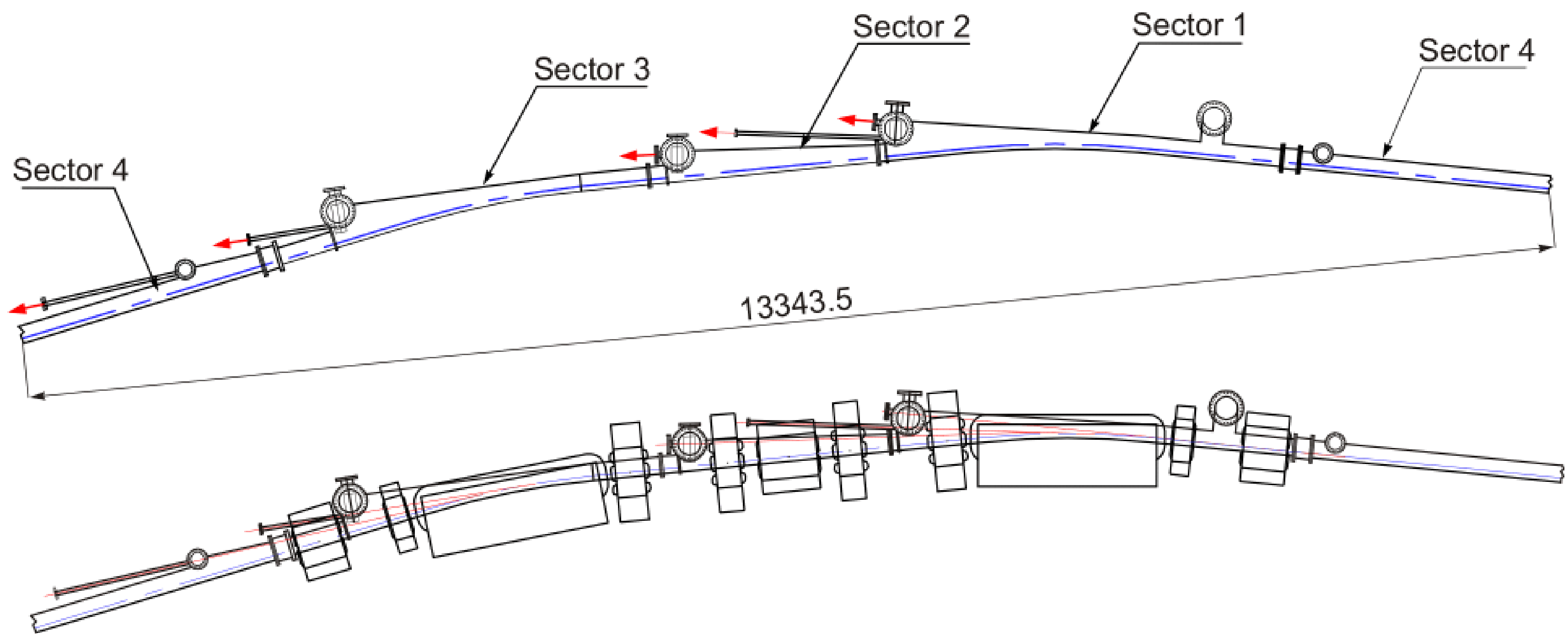

Figure 3.8.1. Standard section of vacuum chamber layout.

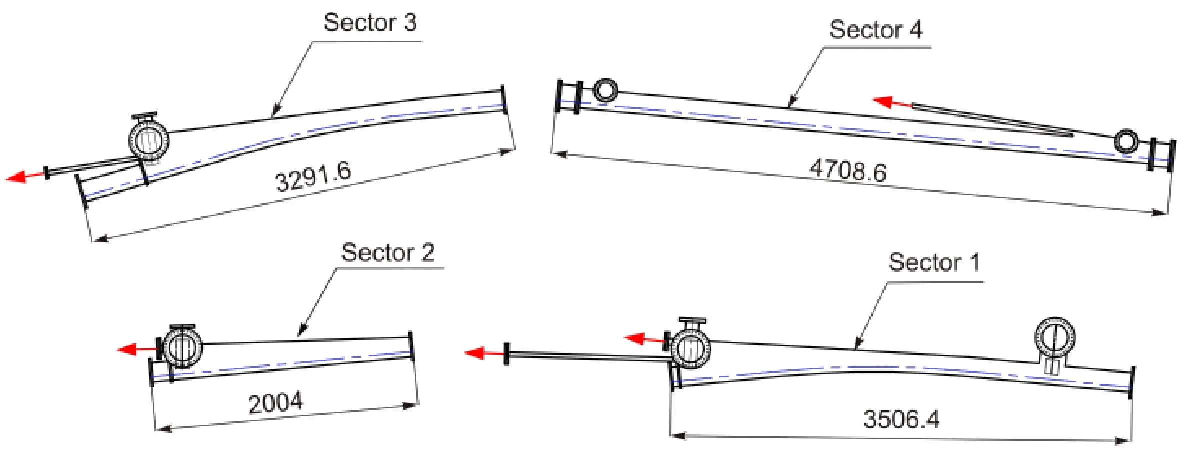

Fig. 3.8.2 Plan view of different sections of vacuum chamber.

A characteristic feature of vacuum chambers in dipole sections is the use of the antechamber design to deal with synchrotron radiation heading problems. The vacuum chamber consists of an electron beam chamber open to an antechamber. In the straight sections where the synchrotron radiation power density is low, the vacuum chamber is without antechamber. The electron chamber geometry is constant through the whole perimeter of the ring, while an antechamber width is variable and depends on the nature of the radiation profile. Fig. 3.8.3 a), b) show the cross sections of the vacuum chamber.

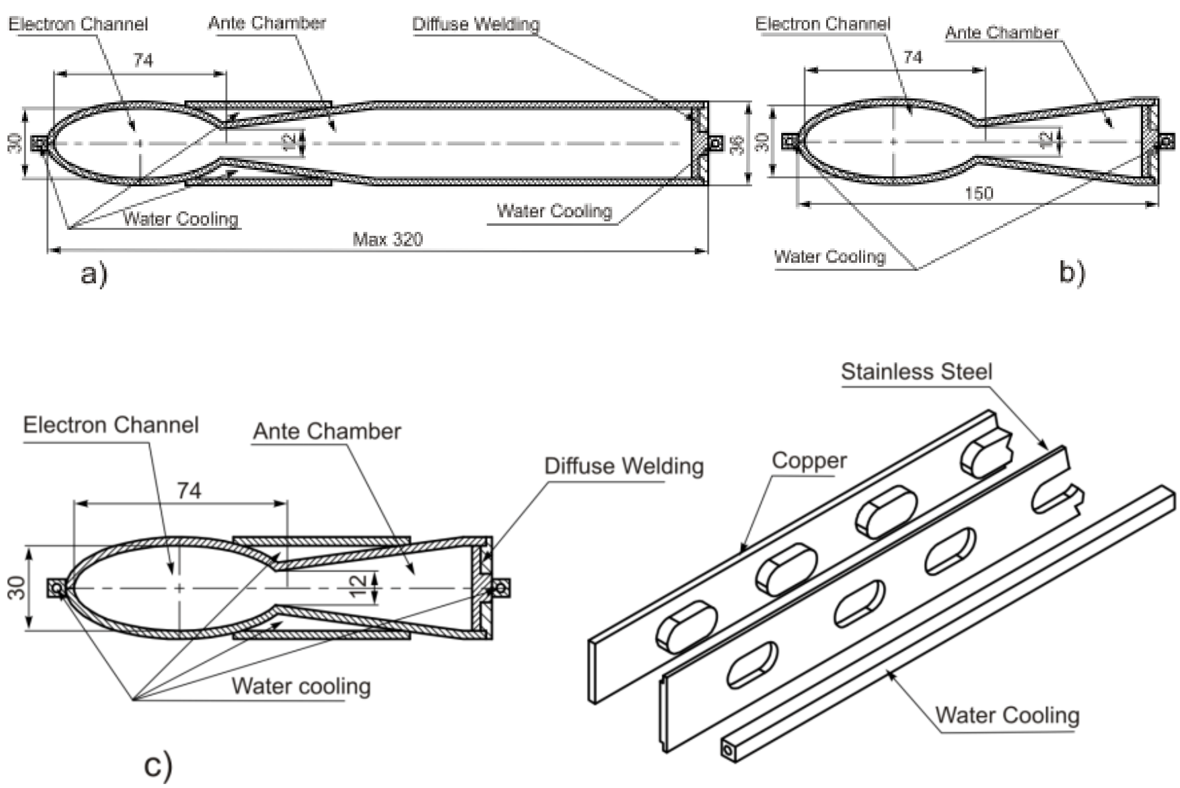

Fig. 3.8.3 Cross-section of vacuum chamber: a) in dipole magnet b) in lenses and c) detailed drawing of chamber vertical wall.

The electron channel of the chamber is implemented in the form of an ellipse with internal dimensions of 30 mm in the vertical plane and 74 mm in the horizontal plane. As seen from the drawing, the electron channel is built of two symmetric halves, which are welded together longitudinally. The profiles of these halves will be achieved through die stamping followed by a subsequent laser trimming of edges. Weld sewing is implemented by using TIG (tungsten inert gas) welding along with the electron beam welding. The first one enables the reduction of possible mechanical deformations, which would arise because of the large depth of electron beam welding.

3.8.2 Water Cooling and Absorbers

For the cooling of the dipole magnet chamber, a water jacket is foreseen. It is formed between the welded plates, placed up and down, and the contour of the main profile. At the two ends of the chamber the water jacket is suppressed by blank flanges, to which pipe connections are welded, in a purpose to supply and remove water. On the rear wall of antechamber and on the front wall of electron channel the rectangular copper pipes, which have a high thermal conductivity, are soldered for effective cooling of these areas. The last elements also increase the rigidity of the chamber.

In a purpose to provide a good thermal contact, windows are milled on the stainless steel rear wall of the antechamber. Copper plates are welded to those windows by means of diffusion welding. When the square cooling copper pipes are soldered, a good thermal contact is provided in an obtained vacuum.

The explosion is shown on figure 3.8.3 c).

For the photon beam extraction from the storage ring, the dipole magnet vacuum chamber has the expanded sections, the end-face of which is blanked off by flange on which the pipe of extraction is welded.

Similar section has also the chamber, where the focusing elements are installed. On these sections the pumping-out nodes are welded on front of the extraction channels. The common view of this junction is shown on Figure 3.8.4.

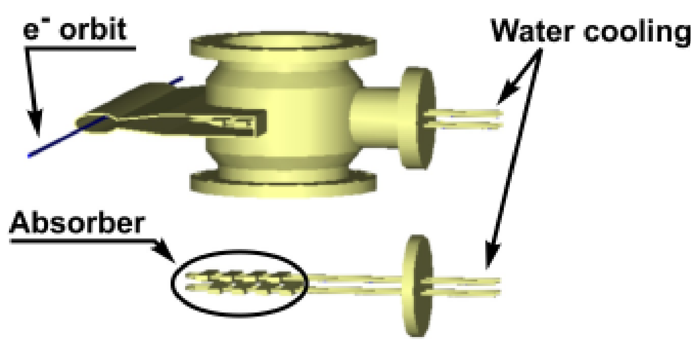

Figure 3.8.4 Pump port with the absorber of vacuum chamber.

The junction unit is a cylinder with three pipes, two of which (the upper and the lower ones) serve for connection of vacuum pumps, and the third one for installation of the cooling absorber. The absorbers are implemented in a form of copper plates with corrugated absorbing surfaces through which the copper cooling pipes pass. The profile of the absorber is implemented in such a way that it allows to close the surface from the direct radiation and to keep open an aperture for photon beam extraction.

3.8.3 Mechanical Properties of the Chamber

In the areas of the vacuum chamber free from the magnetic elements, stiffening ribs made of stainless steel are welded. Calculations show that the maximal deflection in weaker section of the chamber doesn't exceed 0.5 mm. The results of calculation for the straight part of the vacuum chamber and for the vacuum chamber within the dipole magnet are presented in Figure 3.8.5 and 3.8.6 respectively.

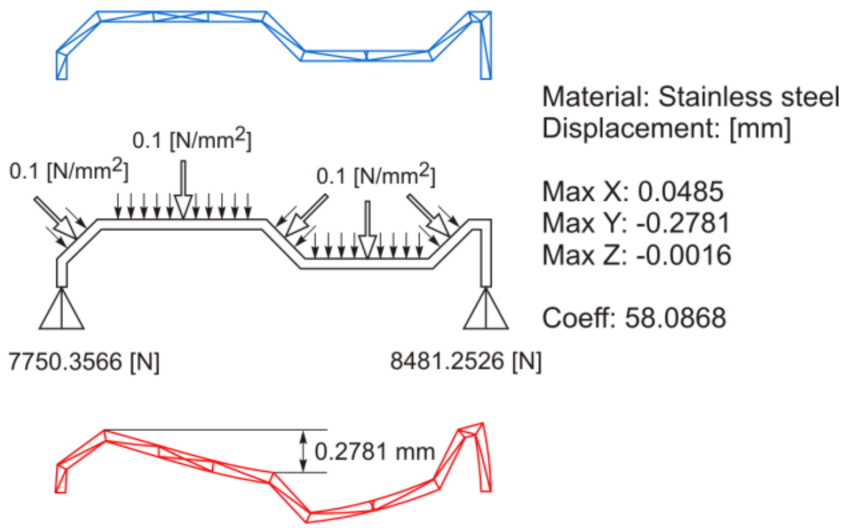

Figure 3.8.5 Straight part vacuum chamber deformation (FEA).

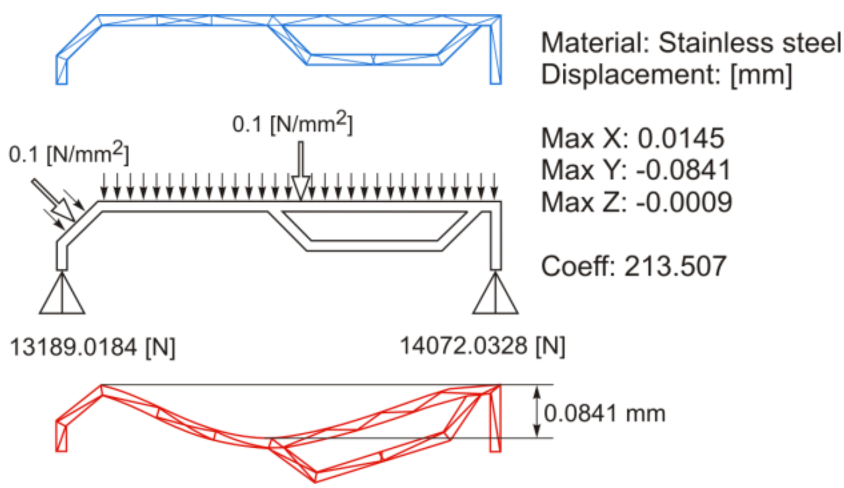

Figure 3.8.6 The dipole magnet vacuum chamber deformation.

Calculations have been done for upper half of the chamber profile. Loading is uniformly distributed and amounts 0.1N/mm², which corresponds to a pressure of 1 atmosphere. The pressure within the chamber is zero. As one can see from the Figure 3.8.6 the section within the dipole magnet is stiffer due to the welded plates, which also serve for the formation of the water jacket. If the maximum deformation of the profile of vacuum chamber in the straight part is ~ 0.28 mm, then within the dipole magnets it equals 0.08 mm, which is quite acceptable.

The vacuum sections are connected with bellow junctions, which serve as flexible elements during the positioning of the sections in one period region. The internal surface of the bellows is protected by thin copper plate. It is fabricated in a form of a cylinder with longitudinal cutouts. All the flange connections in vacuum system of the storage ring have smooth plane butting surfaces, between which a metallic compression with a plane seal is placed. This essentially decreases the impedance, as well as excludes the gap between flange and compressor. In addition, this procedure reduces the tolerances of butt-jointing elements by approximately ±0.05mm in length and ± 0.1mrad in angle.

After the fabrication, the vacuum chamber is subjected to the thorough chemical processing with special solutions and then vacuum annealing is performed. At the ends of the vacuum chamber of dipole magnet on the upper and lower walls the blocks made of stainless steel are foreseen, on which the blocks of BPMs will be fastened.

3.8.4 Pumping System

In accelerators, one of the following three pumping schemes is usually used: autonomous external pumps with relatively low speed, connected to the chamber at free spaces; built-in pumps installed at the most intensive gas load zones of the chamber in combination with the external pumps; manifold pumping system, based on ultrahigh vacuum pumps with relatively high pumping speed. Table 3.8.2 represents the comparative analysis of different solutions for the storage ring vacuum system [4].

Table 3.8.2 Comparative characteristics for pumping schemes.

Solutions	Advantages	Disadvantages
External pumps placed with a step, which is determined from a magnet system structure	1. Minimum cost of the vacuum chamber. 2. Constructive and technological simplicity of the vacuum chamber. 3. Accessibility and simplicity of the pumps maintenance.	1. Significant gradients of residual gas concentration in the chamber sections between the pumps. 2. Significant increase of the average pressure compared to a pressure in a pump zone. 3. High cost of the pumping system and substantial operating expenses.
Built-in and external pumps	1. Minimum possible concentration of residual gas in the chamber. 2. High homogeneity of the pressure.	1. Constructive, technological complexity and high cost of vacuum chamber. 2. Difficulties in built-in pumps access and their maintenance. 3. High cost of the pumping system.
Manifold pumping	1. Minimum possible number of pumps, power supply and control system units. 2. Minimum cost of pumping facilities and operation. 3. Accessibility and simplicity of the pumps maintenance.	Presence of additional elements: collectors and large number of connecting pipelines, which are highly increasing the material capacity Significant increase of the average pressure compared with a pressure in a pumping zone. Significant increase of the overall dimensions of the vacuum section.

As it is seen from the table, in which the features of each of these solutions are summarized, none of these solutions can be observed as optimal, while additional criterions are not considered. The detailed analyses of the obtained results in consideration with economical, production, technological and exploitation factors, allows the option with external pumps for the CANDLE vacuum pumping system to be basic. This solution is the most cost-efficient in the stepwise construction of the complex and is the simplest scheme, which provides the demanded vacuum parameters.
The pressure distribution over the chamber length is given by formulae [5]:

$$P_x - P_0 = \frac{q \cdot \Pi \left(L_x - 0.5 \cdot x^2\right)}{\beta \cdot f^3} \cdot \left(\frac{M}{T}\right)^{0.5};$$

$$P_0 = P_{OH} + \frac{q \cdot \Pi \cdot L}{S_{OH}} + \frac{q \cdot \Pi \cdot L}{3.64 \cdot F}\left(\frac{M}{T}\right)^{0.5},$$

where P_x is the absolute pressure in the x-th cross-section of the chamber, P_0 is the pressure in the branch pipe connecting the chamber and the pump, q is the desorption flow from the unit chamber surface (specific gassing rate), β is the coefficient defined by the vacuum chamber shape, f is the chamber's cross-section characteristic size, M and T are the molecular mass and the gas absolute temperature respectively, Π is the chamber perimeter, F is the area of the branch pipes' cross section in its stick point with the pump, P_{OH} and S_{OH} are the ultimate residual pressure and the pump acting nominal speed respectively.
The fore-vacuum pumping is performed with roughing-down pumps (2 units) and turbo-molecular pumps (16 units) since they have high rate of pumping [6]. This procedure is implemented along with preventing the oil penetration to the high-vacuum channel with the help of cryo-adsorbent. Gate valves are installed on each turbo-molecular pump, whose impermeability is supported by the metal gasket.
The principal pumping of the storage ring vacuum chamber is implemented with titanium sublimation pumps, connected to the photon absorbers. While the primary function of these pumps is to trap the gas from the photon absorbers, each pump offers 1200 liters/s or a total of about 100,000 liters/s for the entire ring.
Titanium sublimation pumps do not pump off methane and argon [7], so 64 StarCell sputter ion pumps are also distributed around the ring. The pumping rate of each station is 150 liters/s. These pumps are also designed for pressure measurement; thus they constitute 64 vacuum-measurement stations. The total amount of pumping of these NEG pumps is 10000liters/s. All the pumps can be isolated from the vacuum system of the ring with the help of gate valves, which have metal seals.

Table 3.8.2 The components of pumping system.

Pumps	Quantity	Pumping rate/unit (liters/s)	Vacuum (Torr)
Fore-vacuum pump	2	25	10^{-2}
Turbo-molecular pumps	16	600	10^{-6}
Titan-sublimation pumps	80	1200	10^{-8}
NEG-pumps	64	~150	10^{-11}

Several procedures are necessary for the vacuum chamber conditioning. When the vacuum chamber and other elements of vacuum system will be constructed, electrochemical buffing will be carried out in order to remove contamination from the surface of metal, smooth the crests of micro-protuberances. Then ultrasound ablution and drying will be carried out. The kilning in vacuum stoves at least at 10^{-5} Torr vacuum is used to remove the stress. In order to check technological process of vacuum creation, laboratory tests are conducted on a special test bench. In a purpose to achieve the required vacuum, if it will be necessary, the chamber can be evenly heated up to 250^{o} C by special heating cover. Afterwards, vacuum chamber sectors under vacuum are cooled to room temperature and then are installed inside of the magnets.

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