PROCESS OF PERFORMING THE ACCELERATING STRUCTURE FOR LINEAR ELECTRON ACCELERATORS

Proces wykonania struktury przyspieszającej do akceleratorów liniowych elektronów

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A b s t r a c t: The article describes technological processes implemented during the production of accelerating structures for linear electron accelerators. In the production of accelerating structures, in order to obtain the expected final parameters of the electron beam, it is necessary to maintain very high accuracy of successive technological operations. Some dimensions of the resonance cavities constituting the basis of the structure should be in accordance with the design documentation, prepared on the basis of previously performed calculations and simulations with the use of programs solving partial differential equations, made with an accuracy of one hundredth of a millimetre. Additionally, due to the need to create a very high vacuum inside the structure the manufacturing of the structure, it is necessary during the production process to follow the cleanliness conditions of the works, specified by the technologist, for some technological operations. Time consuming production stages, expensive materials, complicated technologies using specialized machines and tools cause high costs and thus require the use of continuous inter-operational control. The article presents a new technological solution consisting in making cavities with higher tolerance of dimensions crucial for the electron acceleration process and connecting the cavities by brazing them together with other components of the accelerating structure in a way that guarantees the vacuum in the space where the electrons are accelerated. Until now, diffusion-connected resonators were inserted into a pipe made of stainless steel, which served as a vacuum jacket. The final part of the article describes the method of liquidation of vacuum leaks formed in the soldering process, which, when found, especially in the final stages of production, cause significant losses. It is, therefore, important to ensure that such damage can be repaired such a way that guarantees a vacuum during the entire life of the accelerator.

K e y w o r d s: linear electron accelerator, accelerating structure, vacuum

S t r e s z c z e n i e: W artykule opisano procesy technologiczne realizowane podczas produkcji struktur przyspieszających liniowych akceleratorów elektronów. Przy wytwarzaniu struktur przyspieszających, dla uzyskania oczekiwanych parametrów końcowych wiązki przyspieszanych elektronów, konieczne jest zachowanie bardzo wysokiej dokładności kolejno wykonywanych operacji technologicznych. Niektóre wymiary wnęk rezonansowych stanowiących podstawę struktury winny być, zgodnie z dokumentacją konstrukcyjną, opracowaną na podstawie wykonanych wcześniej obliczeń i symulacji z wykorzystaniem narzędzi informatycznych rozwiązujących równania różniczkowe cząstkowe, wykonane z dokładnością jednej setnej części milimetra. Dodatkowo, z powodu konieczności wytworzenia we wnętrzu struktury bardzo wysokiej próżni, należy podczas procesu produkcji przestrzegać, określonych przez technologa, dla niektórych operacji technologicznych wręcz sterylnych, warunków czystości prowadzenia prac. Czasochłonność etapów produkcji, drogie materiały, skomplikowane technologie z wykorzystaniem wyspecjalizowanych maszyn i narzędzi, to powody wysokich kosztów produkcji i tym samym konieczne jest stosowanie ciągłej kontroli międzyoperacyjnej. Celem artykułu jest przedstawienie nowego rozwiązania technologicznego polegającego na wykonaniu wnęk z większą tolerancją kluczowych dla procesu przyspieszania elektronów wymiarów oraz połączeniu rezonatorów poprzez ich zlutowanie, łącznie z pozostałymi podzespołami struktury akceleracyjnej, w sposób gwarantujący zachowanie próżni w przestrzeni, w której przyspieszane są elektrony. Dotychczasowo rezonatory połączone dyfuzyjnie wsuwane były do rury wykonanej ze stali kwasoodpornej, która stanowiła płaszcz próżniowy. W końcowej części artykułu opisano sposób likwidacji powstałych w procesie lutowania nieszczelności próżniowych, które stwierdzone, zwłaszcza w końcowych etapach produkcji, powodują duże straty materialne, dlatego też istotne jest zapewnienie możliwości naprawy takich uszkodzeń i to w sposób gwarantujący utrzymanie próżni podczas całego okresu użytkowania akceleratora.

S ł o w a k l u c z o w e: akcelerator liniowy elektronów, struktura przyspieszająca, próżnia

Introduction

The main element of linear accelerator, serving for generation of ionizing radiation is the accelerating structure (Fig. 1). Electrons, as being accelerated by electric component of electromagnetic field, are moving along the axis of the structure under a high vacuum (for the structures produced in NCJB, reaching energies of 2 – 15 MeV). The electromagnetic field of high frequency is shaped by the respective internal shape of resonance cavities. Although the process of shaping a field inside the structure is a problem, described by Maxwell equations [9], so it belongs to the domain of physics and electronics, the performance of resonance cavities – the shape of which is calculated by a complicated software – must be implemented by machining process, by the development of machining technology and, successively, by development of the technology of connecting the

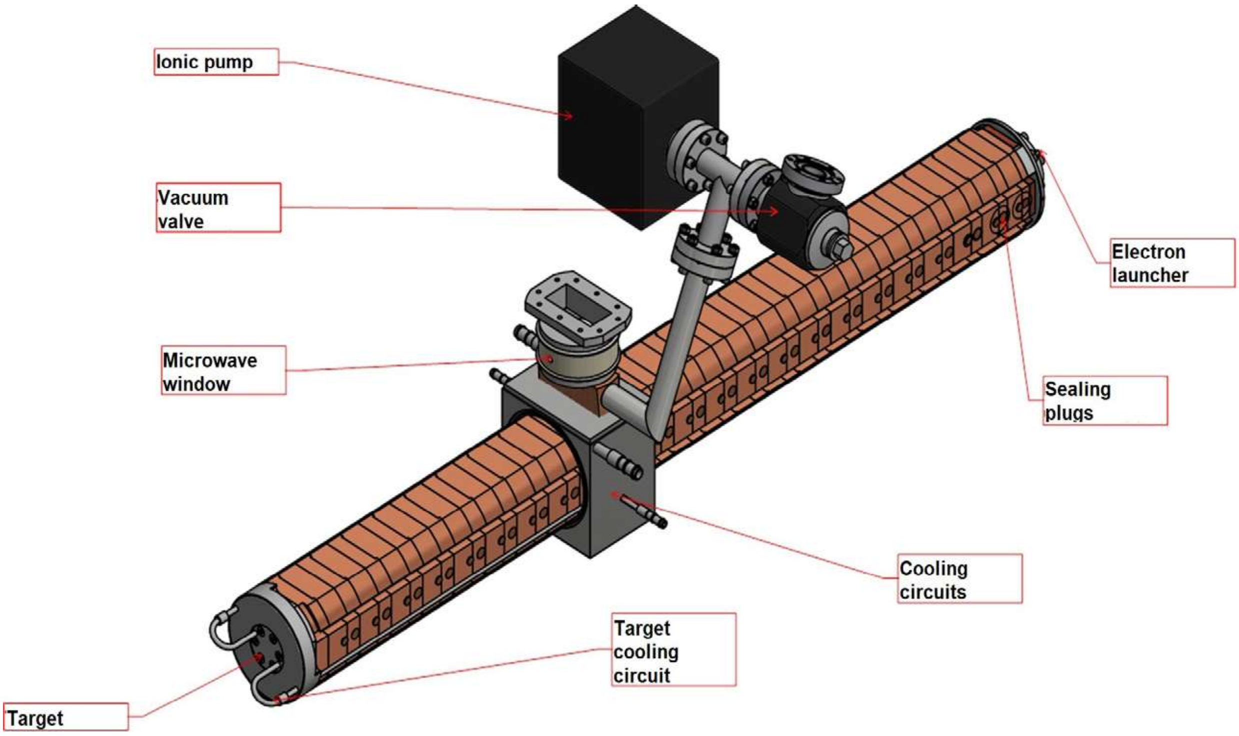

Fig. 1. Accelerating structure

resonance cavities. The beam of the accelerated electrons is introduced outside the structure. If photons are utilized in the anticipated application of accelerator, the beam of electrons falls on the conversion shield which may be built into the vacuum area or be found outside it. In this site, the conversion of electrons and obtaining of a stream of photons takes place.

The total process of electron accelerating occurs in a high vacuum. The temperature is a factor, which has a greatest effect on deterioration of vacuum; it causes liberation of gases from the internal surfaces of the structure. A high capacity of vacuum area, i.e. relatively high internal space, participating in gas desorption does not allow stating that vacuum in the structure has a static nature. Therefore, ionic pumps with the velocity dependent on their size are assembled to each structure.

To have the effective process of keeping the appropriate vacuum level during the structure's work and the employed vacuum pump be efficient, the structure must be vacuum-proof and deprived of contaminations, especially in the upper layers of its inside. Even a small leak may cause damage of electron launcher and, in effect, damage of the structure. To ensure vacuum inside the structure, its mutually connected resonators have been (at NCBJ) for many years slipped to acid-resistant pipe which constituted a vacuum jacket.

This work presents a new solution in two areas. The first one includes a development of the copper machining technology; the mentioned element is a basic material from which the resonators are produced (Fig. 2). The need of developing the discussed technology resulted from the conducted simulation by NCBJ, with the utilization of the newest calculating instruments [10, 11, 12]. As a result of it, the new data concerning the shape of resonance cavities were obtained. From the conducted calculations it is followed that the rise of the precision of certain dimensions of the mentioned cavities would allow obtaining better effectiveness of the acceleration of electrons at lower outlays on their performance. The precision of conducting the measurements of resonators has a direct impact on their own resonance frequency which must be consistent with the frequency of electromagnetic wave, feeding the structure. The frequency of the source of microwave power may be tuned from 2993 MHz to 3002 MHz and this raw range of retuning is used for automatic compensation of the changes in dimensions of resonators, resulting from the changes in their temperature during the work with a beam of electrons.

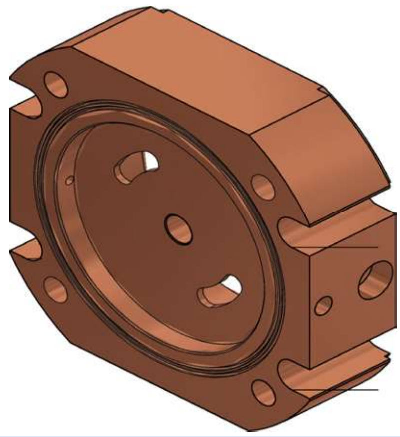

Fig. 2. Cavity

Thus, for example, on the grounds of the conducted simulations, the precision of performing the internal diameter of cavity should amount to +/- 0.02 mm; the depth of accelerating cavity should be equal to +/- 0.01 mm and the length of "nose", constituting the limitation of the acceleration area should be also +/- 0.01 mm. Until now, the submitted above tolerances of dimensions were even twice exceeded. The introduction of selection of the performed cavities was the solution of the discussed problem. As a result of the selection process, about 10% of the produced cavities had to be scrapped.

Additionally, the new programmable machining equipment, as being furnished with the newest tools, guarantee not only the possibility of rising the tolerance of performing the dimensions but also the possibility of decreasing the roughness of the surface, which is significant from the viewpoint of the properties of microwave resonance cavities. The roughness of the surface affects the quality factor of resonance cavities which may be directly translated into the obtained energy of the accelerated electrons per unit of length of the structure.

The second area, presented in this study, is the technology of combining the resonators and the remaining constructional elements of the structure by brazing. The brazing process must ensure the permanent mechanical joining of all elements of the structure with preservation of vacuum in the acceleration area, high electric conductivity of joints, deciding on the quality factor of the structure and preservation of vacuum during the work of the structure with the beam of electron. During the work, the heating of the structure's inside takes place, what causes a considerable difference of temperatures between its inside and outside layers, which are additionally cooled with water flow or by other cooling liquids [6]. The mentioned difference of temperatures cannot cause leakages, infringing the level of vacuum. The brazing (soldering) process of the structure must ensure so reliable joining of its elements as to guarantee the tightness of the vacuum area at the changes of temperature.

Materials, methods and the results of the tests

To obtain the appropriate parameters of the structure and its reliable work, it is necessary to select properly the materials and technological processes, implemented during the whole cycle of production. The materials used in production of accelerating elements, forming and converting the beam of electrons, should have a small expansion coefficient and not deteriorate the level of vacuum. To enable the correct work in the places where high quantities of heat are generated, the materials should also facilitate its quick removal outside so as to limit the changes on the dimensions of resonators. For these ends, the structure is also cooled by a liquid with constant temperature of ca. 40°C.

According to the mentioned above requirements, the oxygen-free copper is the main material from which the resonators, the basic elements of the structure, are constructed (Fig. 2). The contaminations in copper do not exceed 40 ppm; it ensures good conducting parameters and good parameters of heat dissipation; it is so technologically prepared that it does not contain big quantities of residual gases inside. Non-magnetic, acid-resistant steel is a technological material serving for fixing the cavities and other elements of the structure (Fig. 1): microwave window, ionic pump, vacuum valve, launcher of electrons, cooling system and system of leading the beam of electrons to the target. For mechanical joining of the particular elements, Ag-Cu binder is employed; it ensures a reliable combination and does not introduce any organic contaminations to the inside of the structure. Moreover, the melting temperatures of the used solders are so selected as to implement the processes of binding the elements of the structure in few stages. All technological processes must ensure mechanical and electric parameters of the resonators, as being assumed in the construction documentation

• Machining

The process of the structure production is commenced from the production of resonators (Fig. 2), the elements forming and accelerating the beam of electrons. Resonance cavities are performed by machining. The mentioned process was previously carried out in the simple, traditional lathes and milling machines and the parameters of treatment were so fixed that they allowed performing the cavities but it was necessary to carry out their segregation (roughly by measurement of their key dimensions) and then, to measure their own resonance frequency. It was caused by the dispersion of the dimensions of the produced resonators outside the requirements of documentation. The inspection process allowed classifying the groups of the resonators, being produced sufficiently identically as to make the whole structure from them. The passage from simple machining machines to the precise treatment centres (CNC, Computerized Numerical Control) required determination of the sequence of performing the operations as well as correction of the parameters of each operation, that is, a choice of the machining tool and velocity of machining, machine feed and depth of machining. Copper, which is subjected to machining, is very soft (hardness 50 HB). The treatment of such soft material is highly difficult. Adoption of too low value of machining depth may cause that the material would be not cut but squeezed. It is therefore, necessary to employ thicker chip what makes the machining process more difficult. At the same time, the experiments with the knife radius were carried out in aspect of the obtained roughness of the surface. The effects of machining were evaluated by the measurement of some experimentally treated cavities. The preliminary measurement consisted in the inspection of the measurements, and then, own resonance frequency and quality factor of the cavities were assessed. The first reached results allowed obtaining the appropriate dimensions of the cavities, with the expected tolerance – i.e. 0.01 mm (depth of the cavity, length of "nose") and 0.02 mm (diameter of resonator) respectively, at the roughness of the surface Ra of order 0.3 μm, in result of which the quality factor was equal to 5000. After optimization of the treatment parameters, the required precision of dimensions was obtained at roughness Ra 0.11−0.12 μm; after the procedure of cleaning and electro-polishing, the roughness was de creased to Ra 0.07−0.09 μm what allowed exceeding the expected quality factor 9000−10000. As a result of the conducted trials, the targeted technology of machining of the resonators was developed. The mentioned technology contains the control measuring points where checking of the dimensions and/or measurement of the surface roughness is carried out. In the successive stage, the control of microwave parameters of individual resonators is conducted. A positive result of this inspection enables for assembling the cavities into sets. The discussed technological operation is also carried out by the measurement of microwave parameters. As obtaining of the appropriate frequency in the successive accelerating and coupling cavities and of the appropriate distribution of electromagnetic field, requires almost always tuning of each cavity, each resonator has a place left for the elements used in such operation. They have the possibility of changing the expected value. After completion of the whole set of resonators and inlet of high frequency power, checking of the microwave parameters of the set is carried out. At this stage, the resonance frequency, quality factor, electric field distribution and coefficient of coupling the structure with wave line, feeding it with high frequency energy, are preliminarily determined.

Purification before brazing process

The produced and checked resonator, being positively admitted to further assembling, obtains its individual number with the assigned table of mechanical size measurements. A positive reaching of all expected parameters allows chemical preparing of the structure's elements to the process of their mechanical and permanent joining by brazing. Purity of the materials before soldering of the cavities is very important [2, 3]. Dirt and the oxides, generated during the treatment have a negative effect on electric conductivity and decrease the wettability of the solder. The cavities are washed in ultrasonic scrubber in the mixture of petrol and acetone and then, they are rinsed with distilled water. After the mentioned treatment, they are subjected to the electro-polishing. The completion of purification process puts extremely difficult requirements concerning hygiene regime before the operators, implementing the successive stage of the structure production.

Brazing process

Brazing (soldering) is carried out in the horizontal oven where the temperature distribution is controlled by a series of thermocouples. During the brazing, the vacuum in the oven is better than 10^{-5} mbar. The resonators of the structure are completed respectively to the earlier terminated process of microwave tuning. The solder of 1 mm diameter is introduced into the brazing channels. The channels are so shapes as to eliminate the outflow of solder to the inside of the cavity. The parameters of brazing i.e. shape of channels, diameter of solder, composition of the solder and the pressure of the joined resonators have been experimentally selected during the brazing trials. The mentioned trials were performed by soldering of a few resonators. The implementation of the trials was based upon own experience and literature [7, 8]. After brazing, the tightness of the soldered sample was examined by helium detector of leakages and later on, it was cut off for visual inspection of the joints. On the grounds of literature data [2, 3] and with the assumed sizes of vacuum area and the anticipated ionic pumps, it was established that the leak as measured by helium detector cannot exceed value of 10^{-11}mbar x l/s. as a result, the following parameters of the process were adopted:

- Pressure of the joined resonators by momentum 3Nm,
- Application of solder with the composition 0.72 Ag−0.28 Cu,
- Heating of the batch in the oven at velocity of ca. 5°C/min up to the temperature of 768°C and then, slowing down the rate of temperature change and heating up to temperature approximate to 800°C and then, after reaching this temperature, switching off the heating and cooling the batch to its complete cooling down, still at ensured vacuum.

For brazing, the resonators of the structure are twisted with four pins with the utilization of dynamometric key and they are put into the bed of the oven, based upon the ceramic washers, placed in the oven. After reaching the required vacuum in the chamber of the oven, the process of brazing is commenced. After the first soldering, the checking of the quality of brazing and of the tightness of joints is performed using helium detector. Next, the structure is finally tuned and the appropriate sealing plugs are installed; they close the places where the tuning elements were placed.

After their soldering, the sealing plugs (Fig. 3) should ensure the appropriate level of vacuum tightness. The last stage of performing the structure includes their brazing. The mentioned process takes place also in the vacuum oven in such a way as to obtain a certain binding in the sites of the sealing plugs and not cause the disconnection of the earlier combined elements. After the conducted tests until the mentioned stage, the solder with the following parameters was selected: 0.61 Ag – 0.24 Cu – 0.15 In. Its melting temperature is 705°C and

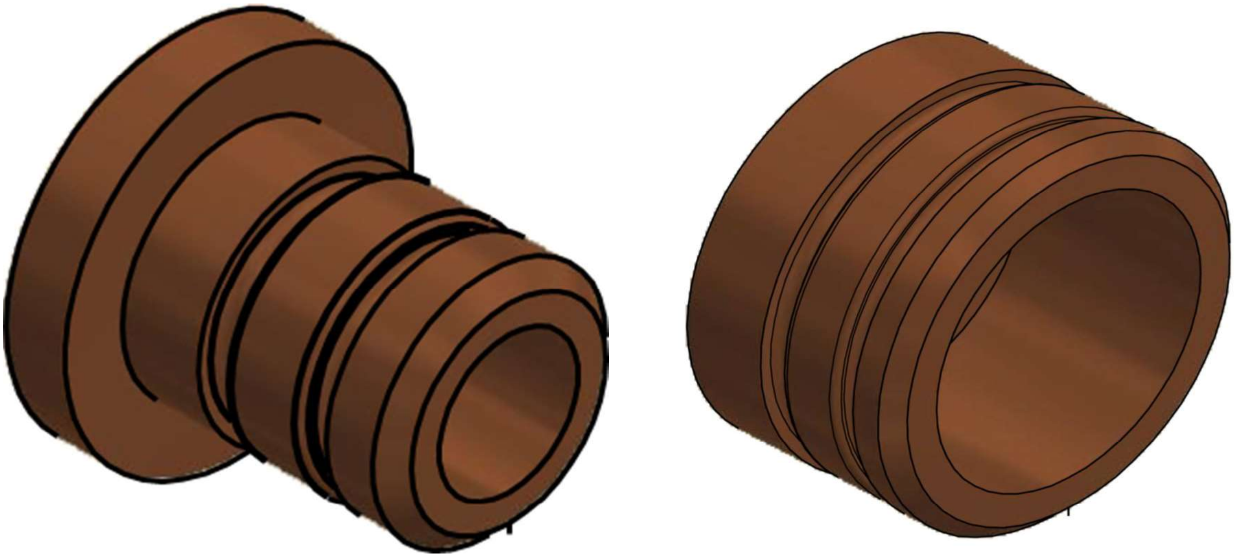

Fig. 3. Sealing plugs

the process of heating and cooling down the structure runs similarly as the previously, with the switching off the heating at temperature of 720°C. After the discussed stage, a final checking of vacuum tightness is performed and in the case of positive result, joining of the launcher of electrons is carried out. During the implementation of the brazing process, it is necessary to observe strictly the temperature and time requirements, described in the technology of brazing. so prepared structure is subjected to thermal treatment [4, 5] and then, microwave treatment in order to degasify it finally. At the end of the described process, the structure is placed in a special stand for testing of the structures [1] where the tests of all its parameters, in particular energy and current of the beam of accelerated electrons are carried out.

• The errors of brazing

Vacuum leak may be practically detected at each stage of the described above process of performing the structure. It is especially expensive in the case of the last stages of brazing or already during the thermal or microwave treatment. Therefore, it has become significant to develop a method for removal of leaks, found during the final stages of performing and treatment of the structure. The reasons for occurrence of leaks may be different. The main reasons are as follows:

- Use of improper material;
- Failure to meet the technologically specified requirements concerning the purity of the surface;
- Failure to keep the parameters, specified in the technology;
- Failures of the equipment during the conducted technological treatments.

It is therefore, important to employ the appropriate materials with certificates and to buy them from certified (proven) suppliers, guaranteeing the parameters, specified in the certificates. The acquired experience, as described in production technology, ensures the appropriate selection of the parameters connected with the preparation of the surface and conducting each stage of the process of the structure production. In the case of the multi-stage diversified and complicated process, making the mistakes is unavoidable and the situations resulting in leak occurrence may happen. On the one hand, automation of the brazing process in vacuum ovens causes a high precision and repeatability but, on the other hand, a complicated construction and automation of the oven may expose the implemented process to the disturbances. Failures of the oven may cause interruption of the brazing process at any moment. It is especially dangerous in the situation when the whole batch has a high temperature and ionic pumps or the systems of their cooling become damaged. Then the loss of vacuum oxidation of the batch may occur. If the temperature is sufficiently high as cause the oxidation process, we are encountered with the leak, caused by generation of oxides on the surfaces of the solder's melting. Such case causes practically a lack of tightness in each resonator. The leaks at the individual sealing plugs occur more rarely; they are caused by defects of material or by human error. The discussed leakages are discovered very often during the thermal or microwave treatment. The costs of production of the structure born up to this stage justify the application of repairing work what, in turned, forced a development of repair methods and technologies.

After having stated leaks, it is necessary to develop, each time, the method for its liquidation, with the consideration of the place of the leakage, size of the leak and technical possibilities of its removal. It is relatively easy to remove the leaks found during the first stages of joining the resonators (after the first stage of brazing). Then, during the second stage, i.e. soldering of the plugs, we place the sealing material in the leakage points; their task is to eliminate the leaks. The problem is more complicated when the leaks are found in the sealing plugs

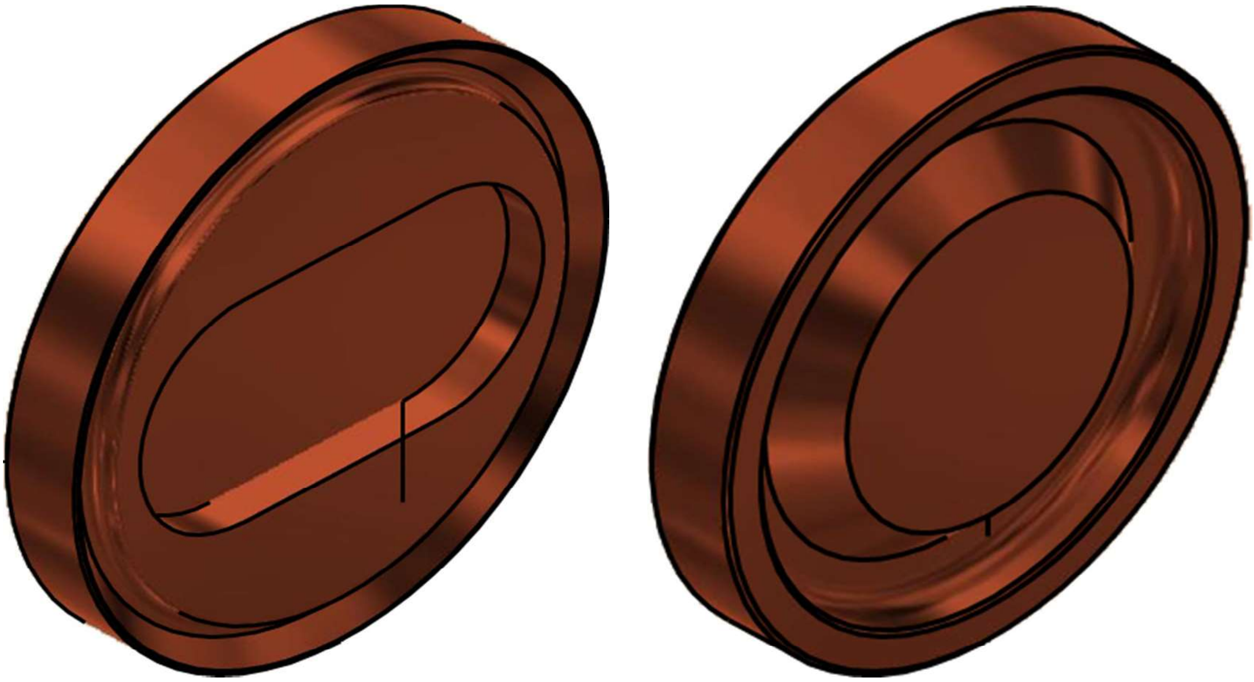

Fig. 4. Additional plugs

sated in the final stages of treatment. In such case, we have to analyse, each time, the site of their occurrence and develop the appropriate shapes of additional plugs and perform their additional brazing. Fig. 4. shows the examples of additional sealing plugs.

During soldering, we have to remember that the conducted process will be the additional process. We have, therefore, to select the technology of its performing, choose not only the shape of the sealing elements but also the composition of the solder and the parameters of brazing and, eventually, correct the successive processes as rto lead to the positive termination of the structure's production.

Conclusions

When utilizing the possessed and acquired experience, owing to the analysis, the conducted tests and the studies and the constant inspection, gradual introduction of automation, we have developed the constructional and technological documentation, allowing the repeatable, effective production of the accelerating structures of linear electron accelerations via the precise production of cavities in numerically controlled machines and vacuum brazing of the structure's elements. The both aims, being presented at the beginning of this paper, have been reached. Thus, as a result of machining operation, the specified, key dimensions (significant for the utility of resonators) are performed with the accuracy of 0.01 mm and 0.02 mm, respectively. The adopted parameters of machining process (the resulting roughness of the surface R 0.11-0.12) together with the later stage of chemical treatment of the resonators guarantee obtaining the microwave quality factor by the cavities, exceeding 10000. The specified conditions of the brazing process in two stages are as follows:

Stage 1 – set of resonators:

- Pressure of the joined resonators with the moment 3Nm,
- Application of the solder with the composition 0.72 Ag – 0.28 Cu,
- Heating of the batch in the oven with velocity of 5°C/min up to the temperature of 768°C , then slowing down the rate of change in the temperature and heating up to the temperature approximate 800°C when the switching heating off and cooling down the batch takes place.

Stage 2 – sealing plugs:

- Solder with the composition 0.61 Ag – 0.24 Cu – 0.15 In,
- Heating and cooling down of the structure as above, with the switching off the heating at temperature of 720°C.

This ensures effective and repeatable mechanical joining of resonators and vacuum leak lower than 10^{-11} mbar x l/s. We should, however, mention that it is necessary to observe strictly the requirements, recorded in the developed technologies, concerning the parameters of the implemented technological processes, what, in effect, allows minimizing the occurrence of defects. In the light of expensive and labour-consuming process of the structure production, the elimination of the losses, caused by the defects of materials, human errors or failures of machines, is very important element of technological process. The additionally developed technology of liquidation of vacuum leaks allowed, several times, to lead to their effective repair. As a result it allowed performing the fully valuable structures which did not require assembling of additional plugs. Relatively low costs of such repair in relation to the losses, resulting form he eventual scrapping of the structure, justify fully such technological process. It is significant that the employed recovering process does not have any negative impact on the expected parameters and vitality of the structure.

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