Features of device cooling in wiggler synchrotron workstations

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Abstract. The construction of the «Siberian Photon Ring Source», the SKIF synchrotron, in Novosibirsk is underway. At the first stage, six research workstations will be created, most of the devices of which work in a high vacuum. Synchrotron radiation is generated by superconducting Wigglers for two stations. The total radiation power is approaching 49 kW, and the power density on the axis is 92 kW/mrad². The high energy density of the beam creates quite difficult conditions for the thermal management of optical elements at the workstations. The article presents specific requirements for cooling devices, an overview of the used and promising cooling systems is made, an example of calculating the temperature, stress and strain distribution in a diamond filter with a thickness of 300 microns using the ANSYS Fluent software package is given.

1. Introduction

Synchrotron radiation (SR) is a universal tool for characterizing the structure of objects in applied and fundamental science: materials science, biology, geology, medicine, and in the study of processes at the nano- and micro-level with times of the order of picoseconds. By the beginning of 2021, there were about twenty working synchrotrons of the 3rd generation and three synchrotrons of the 4th generation in the world: in Sweden, France, Brazil. The designs of their workstations that provide specific research are unique, determined by the time of creation and their purpose. This article will consider the features of the required thermal management of the individual workstation devices related to the specifics of their designs and applications. An emphasis will be placed on modern tasks and conditions.

Currently, the construction of the «Siberian Photon Ring Source» – the SKIF synchrotron - in Novosibirsk is underway. At the first stage, it is planned to create six research workstations. In two of them, the SR is created by superconducting Wigglers, while the total radiation power is approaching 49 kW, and the power density on the axis is 92 kW/mrad². As an example, figure 1 shows the...
schematic of the Workstation 1-5. It shows the main elements of the station. All of them require a special approach at heat management.

![Diagram of Workstation 1-5](image)

Figure 1. Schematic of the Workstation 1-5.

The absorbed power distribution by the Workstation devices is as follows: 1 – 20.3 kW; 2 – 2 kW; 3 – 0.4 kW; 4 – 0.4 kW; 5 – 0.74 kW; 6 – 2 kW. The first heat-loaded element of the workstation channel will be a fixed collimator that forms the geometric dimensions of the SR beam on the subsequent channel elements and dissipates 20.3 kW of power. Typical energy densities in the cut-off beam on such devices (when falling along the normal to the beam) are of the order of 1,000 MW/m² or more, [1]. These are very significant values for heat fluxes, critical for most materials. Therefore, in all devices of workstations, where possible, the absorbing and reflecting surfaces are located at small angles to the beam axis (often less than 10°), which allows reducing the density of the generated heat flow by an order of magnitude or more.

Taking this fact into account, an energy density of the order of 0.03 - 100 MW/m² is dissipated on the remaining devices forming the beam for research, [2–4]. However, the removal of such energies is also a difficult task, complicated by the fact that the devices operate in a high vacuum (10⁻⁸ Pa), as well as by the fact that, as a rule, there are extremely high requirements for the maximum permissible values of thermal deformation of the device optical elements. The requirements for permissible linear deformations associated with the resulting temperature gradients in the body of optical elements can be less than 0.1 microns on length scales of the order of 100 mm. All of the above requires special approaches to temperature management for creating the workstations.

2. An example of technically complex heat management

One of the examples of devices that are difficult for cooling is thermal filters (2, 3 in figure 1), which contain monocystal CVD diamond plates obtained by chemical deposition from the gas phase, with a diameter of 30–90 mm and a thickness of 50–400 microns, [4]. They are always located strictly perpendicular to the axis of synchrotron beam and are designed to output the beam from the high vacuum to the optical systems of the workstation. The heat power density perceived by the first thermal filters reaches 100 MW/m², their purpose is to relieve the subsequent optical elements from the highest thermal loads and somewhat reduce the non-monochromaticity of the beam. Vacuum diamond windows isolate the high vacuum area directly connected to the synchrotron. Here, the heat power density reaches 20 MW/m². Examples of structures proposed by industry are shown on the figure 2, [5, 6].
Figure 2. Photos of SR thermal filters based on CVD-diamond, manufactured by industry, [5, 6].

The choice of a diamond foil as a filter and a vacuum gate is caused by the fact that it is necessary to perceive the radiation incident along the normal and divert it to a large area, not only without destroying material, but also without significant deformations, whose presence violating the uniformity of the beam. The deviation from flatness in the heat-loaded state should not exceed 0.1 microns in the beam aperture. Currently, only beryllium or molybdenum foils can act as an alternative to CVD diamonds. But already at the end of the 20th century, the advantage of diamond filters was established [7, 8]. The reason is the highest thermal conductivity, strength and optical characteristics of the CVD diamond foils.

Another significant problem in such a device is to ensure a sufficiently low thermal resistance between the diamond filter and the main heat-removing structure while maintaining the integrity and flatness of the diamond window located in a high vacuum. There can be several solutions: soldering of diamond foil to copper, «dry» pressing to the parts with a specially selected thermal expansion, and the usage of special contact coatings, [1, 4–6].

3. Methods of cooling
In the literature about thermal management devices, channel cooling methods are most often described. The characteristic transverse dimensions of the channels are significantly more than 1 mm, the length is more than 10 mm. This is due to the fact that: 1) the experience of the manufactured operating devices presented in the literature was published only in the last century, 2) only the most heat-loaded devices, the total dissipate heat power of which is more than 1–10 kW of the order of magnitude, are more often described.

However, the thermal management of all types of devices used in workstations cannot be carried out only by a channel cooling scheme. For example, for relatively small devices, such as thermal filters, or for optical systems, such as monochromators, much more compact cooling schemes should be used. And these are mini channel systems. Examples of such cooling systems used in workstation devices are presented in [1, 9–13]. Figure 3 schematically shows typical examples of two mini-channel cooling systems of monochromators with characteristic geometric dimensions. On the left, the cooling system is made in the metal adjacent to the body of the monochromator, on the right – the cooling system is made directly in the body of the silicon monochromator. The choice of metal may be due to the fact that the water pressure in the mini channels can cause significant deformations of the monochromator, especially in the boiling condition. Other cooling schemes in the stations under consideration are not described in the literature.
Figure 3. Channel cooling systems for highly heat-loaded optical elements. 
Left: A view of the finished monochromator (top), with an incomplete water collector (right), and mini-channels located under the monochromator, (left) before gluing and cutting to size, [12]. On the right: minichannels directly in a silicon monochromator, [10].

There are 4 typical schemes of miniature high-efficiency heat management systems with forced cooling. Table 1 shows the capabilities of the modern miniature cooling systems with the maximum values of thermal characteristics demonstrated in the laboratory conditions over the past 25 years [21]. For each of the cooling techniques, a characteristic work is first presented, in which typical large values for both heat exchange parameters are demonstrated: the heat transfer coefficient and the maximal specific heat flow. Then the work with the maximum value of the specific heat flow is presented. The table 1 shows that currently only channel and mini-channel circuits are able to meet the full requirements for such tasks.

Table 1. Presentation of the current capabilities of promising cooling methods (water).

| Cooling method        | $h$, kW/(m²K) | $q^*$, MW/m² | Authors                                  |
|-----------------------|---------------|--------------|------------------------------------------|
| by jets               | 280           | 18.2         | Overholt et al., 2005, [14]              |
| by jets               | –             | 43           | Butterfield &., 2019, [15]              |
| by spray              | 120           | 20           | Cebo-rudnicka 2016, [16]                 |
| by spray              | –             | 65           | Vondran et al., 2012, [17]              |
| by minichannels       | 134           | 48           | Calame, 2007 и 2009,[18]                |
| by minichannels       | –             | 276          | Mudawar et al., 1999, [19]              |
| by shear driven liquid film | 300         | 12           | Kabov et al., 2018,[20]                 |

The computation features of the flow modes, heat exchange, and hydraulic resistance of a two-phase flow in mini-channel and micro-channel systems, as well as the classification of channels by size, can be found in [22–28].

4. Features of heat transfer in workstation devices
One of the significant features of heat transfer is the presence of thermal contact resistances between the optical element and the cooling system. Moreover, the optical device is often placed in a vacuum. Next, the example of the temperature distribution calculation depending on the height in the central section of a diamond filter is given. The thickness of the diamond filter is 300 microns, and the diameter is 70 mm. The ANSYS Fluent package is used for modeling. The coordinate center is located in the geometric center of the calculated area. The $z$-axis is directed upwards, parallel to the gravity vector and opposite to the direction of the coolant flow. The $y$-axis is directed perpendicular to the flanges and the diamond plate (figure 4, left). The computational geometric scheme is shown in figure 4.
Here we described two test calculations, so the dimensions of the cooling water channels and collectors have not yet been optimized. The heat flux density at the first calculation for the part of the filter open to SR is 106 MW/m². A variant of an extremely loaded thermal filter that does not work in a package with other filters is calculated. Cooling takes place by minichannels with a size of 0.5×1 mm. The cooling system has one input and one output channel with a size of 2.6×2.6 mm. The maximum water velocity is 27 m/s at a pressure of 5 atm. The water flow rate is 7.0 l/min. The dependence of the diamond plate properties on temperature (thermal conductivity and heat capacity) is taken into account in the calculations. The calculation results are shown in figure 5, on the left. A central region of the filter reaches 2000 °C, while the cooled periphery has temperatures of about 500 °C when thermal contact resistance between diamond and copper is not reduced, as well as the intensification of heat transfer is not used. However, temperatures of 560 °C and 150 °C are acceptable [6].

![Figure 4. The computational geometric scheme for a thermal diamond filter. On the left is a cross-section. On the right – the geometry of the mini channels.](image)

**Figure 4.** The computational geometric scheme for a thermal diamond filter. On the left is a cross-section. On the right – the geometry of the mini channels.

![Figure 5. Calculation results. On the left is the temperature T (0, 0, z) in the central section of the diamond heat filter for a heat flux density of 10.6 kW/cm². On the right – for a variable heat flux density of 1.35 kW/cm² – 1.5 kW/cm².](image)

**Figure 5.** Calculation results. On the left is the temperature T (0, 0, z) in the central section of the diamond heat filter for a heat flux density of 10.6 kW/cm². On the right – for a variable heat flux density of 1.35 kW/cm² – 1.5 kW/cm².

The results of similar calculations for the second case are shown on the figure 5, right. The heat dissipation on the filter part open to the SR is 1290 W. The specified heat flux is inhomogeneous and amounts to 1.35 kW/cm² – 1.5 kW/cm². The heat flux value was determined during experiments at Budker Institute of Nuclear Physics SB RAS. At the entrance of the channels the water temperature is 17°C, and the water pressure is 5 atm. The water flow rate is 7.0 l/min. The outlet water temperature is
19.6 °C. In the case of real heat flux of 1.35 kW/cm² – 1.5 kW/cm², the central region of the CVD diamond can reach temperatures of 342.6 °C, while the cooled periphery (in the mini-channels cross-section plane) has temperatures of no more than 31.4 °C. Calculations show that this thermal load is quite acceptable for the filter.

In addition to thermal calculations, it is also necessary to take into account thermal deformations that can lead to the diamond filter destruction. The calculated 3D-temperature distribution of a CVD diamond is used to calculate the deformations. The maximum equivalent stresses at the CVD diamond were 842.7 MPa, figure 6. The stated tensile strength for diamond films is 1200 MPa. That is, according to the stresses shown above, the configuration of mini-channel water cooling allows not to exceed the tensile strength for heat generation on the filter part open to SR, 1290 W. Figure 7 shows the total deformation distribution in CVD diamond in mm. The maximum value is 1.85 microns.

![Figure 6. Equivalent stress (von-Mises) distribution in Mpa in diamond plate Ø 70mm × 300 μm.](image)

![Figure 7. Total deformation distribution in mm in diamond plate Ø70mm × 300 μm.](image)

Conclusions
Providing thermal management of any elements of Workstations using SR is a unique, complex, non-typical task, due to the high energy density in the beam, vacuum presence and specific requirements for the thermal deformations.

Channel cooling schemes are widely used for thermal management. However, monochromators or thermal filters require miniature cooling scheme. For this purpose, mini- or micro-channel cooling can be used.

Numerical 3D-calculations of the thermal diamond filter of the SKIF synchrotron workstation 1–5 are performed. An effective cooling option for a CVD-diamond thermal filter using mini-channels is presented, with the maximum temperature of the diamond plate (342.6 °C) and thermal stress (842.7 MPa). Limit values for temperature (500–600 °C) and strength limit (1200 MPa) are not exceeded.

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