Device cooling features in wiggler synchrotron workstations

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Abstract. Construction of the 4+ generation Siberian circular photon source (SKIF synchrotron) has started in Novosibirsk. It will initially be equipped with six research workstations. For two stations, synchrotron radiation is generated by superconducting wigglers, whose radiation power approaches 49 kW, and the power density on the axis is 92 kW/mrad². Most of the optical devices of the stations operate in a vacuum. The high energy density of the synchrotron beamline and the requirements for the values of thermal deformations lead to difficult conditions for the thermal management of optical elements. The article provides an overview of the applied and promising cooling systems; an example of a 3D calculation of a thermal diamond filter of workstation 1-5 is given, the limit for the thermal load of the filter, at which the temperature of the diamond plate will not exceed 600 °C, is estimated.

1. Introduction

Synchrotron radiation is a universal tool for characterizing the structure of objects in applied and fundamental science: materials science, biology, geology, medicine, in the study of processes at the nano- and micro-levels with characteristic times of the order of peak seconds. This allows the study and control of the growth of graphene on molten copper in real-time, the real dynamics of the evolution of materials in fuel cells, and the latest accumulators, [1-2]. By the beginning of 2021, there were about twenty working synchrotrons of the 3rd generation in the world, 3+ synchrotrons in the USA, and three synchrotrons of the 4th generation: in Sweden, France, and Brazil. The designs of their workstations are unique and determined by the time of creation and purpose. This article covers the features of the required thermal management of optical devices of workstations associated with the specifics of the Wiggler synchrotron radiation and their application.

Currently, the construction of the 4+ generation Siberian circular photon source with an energy of 3 GeV, which has the minimum emittance among all existing light source facilities and reaches the diffraction limit at a photon energy of 1 keV. At the first stage, six research workstations will be created. In two of them, the radiation beamline is generated by superconducting wigglers, with a total radiation power of 49 kW and with a power density on the axis of 92 kW/mrad².
The composition and distribution of the absorbed power over the optical devices of station 1-5 are as follows: primary collimator of 20.3 kW; thermal diamond filter unit of 2 kW; block of vacuum diamond windows of 0.4 kW; block of heat filters made of silicon carbide of 0.4 kW; silicon carbide vacuum window unit of 0.74 kW; silicon wafer of 2 kW, and monochromator mirror of 0.1 kW. All optical elements require a special approach in thermal management. The first heat-loaded element of the channel of the workstation is a primary collimator, which forms the geometric dimensions of the beamline for the subsequent elements of the channel. Typical energy densities in a cut-off beam on such devices (when incident along the normal to the beam) are of the order of 1,000 MW/m² or more, [3]. These heat flux values are critical for most materials. In optical devices of workstations, where possible, the surfaces absorbing and reflecting radiation are located at small angles to the flow axis (often less than 10°), which reduces the density of the released heat flux by an order of magnitude or more.

The use of such approaches and the sequential dissipation of the beamline power allows the achievement of the value of dissipated energy density of about 0.03 – 100 MW/m² on the remaining optical devices, [4-6]. However, the removal of such energies is not an easy task because optical devices are located in a vacuum, as well as due to extremely high requirements for the maximum permissible values of thermal deformation of optical elements of devices. For example, the permissible linear deformations associated with the emerging temperature gradients in the body of the optical elements can be less than 0.1 μm at length scales of the order of 100 mm. All of the above requires special approaches to temperature management when creating workstations.

2. Example of thermal management of vacuum diamond windows and heat filters

When synchrotron radiation is extracted from a high vacuum, vacuum windows made of beryllium, molybdenum, or CVD diamond foils are used. At this point, the synchrotron radiation is still quite powerful, and the windows are always located strictly perpendicular to the axis of the synchrotron radiation due to the requirement that there should be no distortion of the beamline image. This imposes high requirements both on the strength and thermal deformation of the window material and on its thermal conductivity, which should allow heat to be transferred to the body of the vacuum flange. At present, it is preferred to use diamond vacuum windows containing single-crystal CVD diamond wafers obtained by chemical vapor deposition, 30-90 mm in diameter and 50-400 μm thick, [7]. Thermal filters are designed to remove a part of the beam power, which ensures the operability of the vacuum windows, as well as some reduction in non-monochromaticity of the beamline. The optical requirements for them are as high as for the windows. The thermal power density perceived by the first heat filters reaches 100 MW/m². The density of the thermal power dissipated on the vacuum windows reaches 20 MW/m². Examples of industrially used structures are presented in Figure 1, [7-8].

The choice of diamond foil as a filter and a working vacuum seal is caused by the following: 1) it is necessary to perceive the radiation incident on the normal and remove the dissipated heat to a large area, 2) the destruction of the material and the presence of any type of structural defects in it are not be allowed, 3) significant deformations (deviation from flatness in the heat-loaded state should not exceed 0.1 μm in the beam aperture), violating the beam homogeneity, are not be allowed. The reason for the predominant use of diamond foil is the highest thermal conductivity, strength, and optical characteristics of a foil made of single crystal CVD diamonds. At the end of the 20th century, the advantage of diamond filters over other materials was recorded, [9-10].

Figure 1. Industrial CVD-based vacuum X-ray windows, [7-8].
Another significant problem in such a device is the provision of a sufficiently low contact thermal resistance between the diamond foil and the main heat sink structure while maintaining the integrity and flatness of the diamond window in a vacuum. There can be several solutions: 1) soldering diamond foil to copper, 2) "dry" pressing to parts with specially selected thermal expansion, 3) application of special contact coatings, [6-8, 11]. Soldering provides ideally low contact resistance and sealing, but is very specific due to the large difference in thermal deformations of structural elements. In addition, brazing has proven to be extremely corrosive. The "dry" clamp turned out to be relatively metal-consuming due to the reduced thermal conductivity of the materials of the structural elements. The use of special coatings on CVD-diamond and related materials, such as sputtering film packs, is an extremely expensive and specific approach. However, coating a diamond foil or mating part is almost always used.

3. Methods of cooling
In the described practice of thermal management of optical devices using synchrotron radiation, channel cooling methods are most often presented. This is since: 1) in most of the literature, the experience of operating devices manufactured in the last century is presented, 2) the most heat-loaded devices are often described, the total absorbed thermal power of which, in order of magnitude, is more than 1-10 kW. The characteristic transverse dimensions of the channels in these devices are significantly larger than 1 mm, the length is larger than 10 mm.

However, thermal management of all types of devices used in optical elements of workstations cannot be carried out only by a channel cooling scheme. For example, for relatively small devices such as thermal filters, or optical systems such as monochromators, much more compact cooling schemes should be used. These are mini- and micro-channel systems. Examples of such cooling systems for optical devices are presented in [11-15]. Figure 2 schematically shows typical examples of two mini-channel cooling systems for monochromators with their characteristic geometric dimensions. On the right, the cooling system is made of metal adjacent to the body of the monochromator, on the left, the cooling system is made directly in the body of the silicon monochromator. The choice of the metal is due to the strength characteristics of the material since the water pressure in the mini-channels can cause significant deformations of the monochromator, especially during boiling. There are no other cooling schemes in the synchrotron workstations described in the literature.

Table 1 shows the capabilities of several modern cooling systems in use, with a set of maximum demonstrated thermal characteristics. Here, in comparison, the capabilities of mini-channel systems are shown to remove heat fluxes of the order of 10 MW/m² not only in boiling water or HFE-7100 mode but also with quite competitive single-phase cooling. Here and in [29], demonstrated mini-channel systems are not inferior to other cooling schemes: pressure jets, spray or an ultrathin film subjected to a strong shear by an air flow, [18]. The features of flow modes, heat transfer, the
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 [30-36].

Table 1. Mini-channel cooling capabilities.

| Cooling system                      | Liquid | Boiling | \( h \), kW/(m\(^2\)°K) | \( q'' \), MW/m\(^2\) | First author                |
|------------------------------------|--------|---------|--------------------------|------------------------|----------------------------|
| pressure jet                       | water  | yes     | 280                      | 18.2                   | Overholt, 2005, [16]       |
| spray                              | water  | yes     | 120                      | 20                     | Cebo-rudnicka 2016, [17]   |
| Shear driven liquid film           | water  | yes     | 300                      | 12                     | Kabov, 2018, [18]          |
| Macro- and mini-tubes              | water  | yes     | -                        | 276                    | Mudawar, 1999 [19]         |
| mini-channels                      | water  | yes     | 134                      | 48                     | Calame, 2009 [20]          |
| mini-channels                      | water  | yes     | 67                       | 15.0                   | Hirshfeld, 2006 [21]       |
| mini-channels                      | water  | yes     | 260                      | 14.7                   | Zhu, 2014 [22]             |
| mini-channels                      | water  | yes     | 630                      | 13.5                   | Paleo, 2017 [23]           |
| mini-channels                      | HFE-7100 | yes  | 55                       | 11.3                   | Sung, 2006 [24]            |
| mini-channels                      | water  | yes     | 295                      | 10.7                   | Kalani, 2015 [25]          |
| mini-channels                      | water  | yes     | 32                       | 10.2                   | Li, 2017 [23]              |
| mini-channels                      | water  | no      | -                        | 10.1                   | Steinke, 2006 [27]         |
| mini-channels                      | HFE-7100 | no  | -                        | 3.1                    | Sung, 2008 [28]            |

4. Numerical simulation of thermal diamond filter
A distinctive feature of heat transfer in these optical devices is the presence of vacuum thermo-contact resistances between the optical element and the cooling system. The following is an example of numerical simulation using the ANSYS Fluent fluid simulation software of temperature distribution in the central section of a diamond foil with a thickness of 300 μm and a diameter of 70 mm, depending on the height. The center of coordinates is in the geometric center of the computational domain, the z-axis is directed upward, parallel to the gravity vector and opposite to the direction of the coolant flow, and the y axis is directed perpendicular to the flanges and the diamond foil (Figure 3, left). The geometrical scheme is shown in Figure 3, the mini-channel diagram is shown in Figure 3 on the right. There is a liquid metal layer of 0.5 mm between the diamond foil and copper flanges with 35x8 mm windows. Liquid metal is used to seal the vacuum connection and reduce significantly the thermal resistance. Synchrotron radiation beamlines with a size of 30 mm horizontally and 3 mm vertically are directed to the center of the diamond plate. This article discusses a test numerical simulation in which the dimensions of the channels of the cooling water have not yet been optimized and are not final. The task of the calculations was to estimate the limiting value of the heat flux at which the temperature of the diamond foil does not exceed 600°C. Heat fluxes are defined uniformly: 1.378 kW/cm\(^2\), 1.667 kW/cm\(^2\), 1.833 kW/cm\(^2\), and 2.0 kW/cm\(^2\). The total powers released on the surface of the diamond filter are 1240 W, 1500 W, 1650 W, and 1800 W, respectively. Water cooling takes place using 0.5x1 mm mini-channels, located inside copper flanges, the dimensions of the inlet and outlet channels are 2.6x2.6 mm.
The computational mesh consists of 4.68 million elements, with inflation near the channels. The dimension of mesh elements inside the mini-channels is 125 µm. The non-stationary k-omega model turbulence model was used. The numerical simulations took into account the thermal conductivity and heat capacity $C_P$ of the diamond filter. Since the thermal diamond filter will be located in a vacuum, the emissivity of $0 \leq \varepsilon \leq 1$ and the ambient temperature of 22°C were set at the outer boundaries. The value $\varepsilon = 0.02$ was defined for polished copper flanges; $\varepsilon = 0.02$ was defined for diamond foil [37]. The water supply pressure at the inlet was 5 atm, the water temperature was 17°C.

Numerical simulation has shown that for a given heat flux of 1.378 kW/cm$^2$ (total power of 1240 W), the maximum temperature inside the diamond plate will be 322.6°C. The temperature on the walls of the channels did not exceed 31.6°C, the maximum temperature of the liquid metal was 128.1°C. The cooling water flow rate was 9 l/min. Numerical simulations for all defined heat fluxes are shown in Table 2. It can be seen from the table that the limiting value of the heat flux for the selected geometry of the cooling system is slightly more than 2.0 kW/cm$^2$.

Figures 4 and 5 show the temperature distribution inside the diamond filter in the section $y = 0$ and the temperature profile $T(0,0,z)$ along the height of the CVD diamond. The dependence of the maximum temperature $T, ^\circ C$ inside the diamond filter on the total power $Q$ (W) absorbed by the heat filter is well approximated by a polynomial of the second degree:

$$T_{\text{MAX}} = 34.837 + 0.1167\cdot Q + 9.31\times10^{-5}\cdot Q^2$$

| Heat flux density, kW/cm$^2$ | Total power, W | Max. temperature in CVD diamond, $^\circ$C | Max. temperature in liquid metal, $^\circ$C | Max. temperature of channel walls, $^\circ$C |
|-----------------------------|----------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 1.378                       | 1240           | 322.6                                    | 128.1                                    | 31.6                                     |
| 1.667                       | 1500           | 419.9                                    | 154.9                                    | 34.4                                     |
| 1.833                       | 1650           | 480.2                                    | 170.9                                    | 36.1                                     |
| 2.000                       | 1800           | 546.8                                    | 187.2                                    | 37.9                                     |

Table 2. The influence of boundary conditions on temperature.
Figure 4. Profile of the temperature $T(0,0,z)$ in diamond filter Ø70 mm x 0.3 mm.

Figure 5. Temperature distribution $T(x,0,z)$ in °C in diamond filter resulting from heat load of 1800 W applied in the center of the window (beam footprint: 30 x 3 mm, window thickness: 0.3 mm).

5. Conclusion
- Providing thermal management of optical elements of workstations using synchrotron radiation is a complex, non-typical task. This is due to the high energy density in the beamline, the presence of most of the devices in a vacuum, and high requirements for the values of thermal deformations.
- Most often, channels are used for thermal management of optical elements when using synchrotron radiation. However, some optical elements, such as monochromators and thermal filters, require an efficient but much more miniaturized cooling system.
- Numerical 3D simulations of the thermal diamond filter of the workstations 1-5 of the SKIF synchrotron have been carried out. The possible limit on the thermal load of the filter, at which the temperature of the diamond foil does not exceed 600 °C, has been estimated.

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