**EURASIAN JOURNAL OF MATHEMATICAL AND COMPUTER APPLICATIONS**
ISSN 2306–6172
Volume 13, Issue 2 (2025) 105 – 111

# INFLUENCE OF COOLING WATER FLUX ON THE TEMPERATURE OF THE VACUUM WINDOW COMPONENTS OF NOVOSIBIRSK SYNCHROTRON WIGLER STATIONS

**Vinokurov V.V., Vinokurov V.A., Pukhovoy M.V. [1], Kabov O.A.**

**Abstract** A 3D-modeling of the changes in the temperature field of the most important elements of the wiggler workstation vacuum windows of the Siberian Circular Photon Source SKIF synchrotron was carried out with a decrease in the pressure of cooling water and the window structure water flow rate, up to an emergency stop of the pumping station. It has been established that if the pumps are turned off, the maximum temperature in the diamond foil will rise above 372°C, which can cause recrystallization of the diamond and rupture of the foil. At the same time, boiling will not occur on the minichannel walls. However, the temperature in the liquid metal will increase by 37°. This can significantly increase the diffusion of liquid metal components into the polycrystalline copper flange and diamond foil, which can also lead to rupture of the foil. Recommendations for preventing these accidents are presented.

**Key words:** cooling system, mini-channel, Siberian Circular Photon Source SKIF, Synchrotron.

**AMS Mathematics Subject Classification:** 76B47.

**DOI:** 10.32523/2306-6172-2025-13-2-105-111

## 1 Introduction

A synchrotron is one of the types of resonant cyclic accelerators. Its distinctive feature is that during the acceleration of particles, the beam orbit remains of a constant radius, and the leading magnetic field of the bending magnets, which determines this radius, increases with time. The Siberian Ring Photon Source (SKIF) is a source of synchrotron radiation of the "4+" generation with an energy of 3 GeV and an emittance of 75 rad, under construction in Siberia in the science city of Koltsovo (Novosibirsk region, Russia). At the moment, the creation of the main equipment for beam formation is being completed, the development of the first stage workstations has been completed, and work is underway to prepare for the installation of the booster storage device. The first scientific work at these stations will be carried out in 2025.

However, the "4+" generation requires new approaches to the cooling system of all workstation optical elements, the heat dissipation in which will increase significantly [1]. The hard radiation beam for a number of workstations is formed as follows. The wiggler device, interacting with the accelerated charged particles in the ring source, forms a synchrotron beam, which is brought out tangentially to the ring source in the direction of the workstation. Even in the high vacuum region, part of the hard radiation from the synchrotron beam is absorbed by special devices of this workstation, releasing heat. For example, the first heat-loaded element will be a collimator, which forms the geometric dimensions of the beam onto subsequent channel elements and dissipates a power of 20.28 kW. The most important stage of beam formation from the point of view of heat removal from radiation absorbed by optical elements

[1]Corresponding Author.

is the operation of a thermal filter and a vacuum window that separates the high-vacuum part from the rest of the workstation, which, in fact, forms the required working radiation beam for the samples under study. Absorption of part of the hard radiation by the material of the above-mentioned devices is necessary to reduce heat generation in subsequent devices and test samples. The choice of the materials, vacuum window design and optimal cooling method for this optical element is the most important task, which is solved individually for each specific workstation [2-6]. This task must be performed using 3D-numerical modeling.

When developing the wiggler stations of the SKIF synchrotron, a new version of the vacuum window has been proposed and fully developed [6,7], the peculiarity of which is the use of a liquid metal film, 0.5 mm thick, between copper flanges and CVD-diamond foil, which serves as a window. The purpose of this film is to significantly reduce the thermal resistance between these elements. However, one important question about safe operation still required answers: what are the limits of temperature loads on the elements of the optical vacuum window in the event of possible emergency situations or changes in cooling water flux. When operating real optical devices, it may be necessary to both vary the water flux and make a sharp change in the operation of the pumping equipment. This article is dedicated to the answers on this topic.

## 2 Physics-mathematical formulation of the problem

Schematics of the CVD-diamond vacuum window (CVW), proposed by the authors earlier [6,7], is presented in Fig. 1. The main optical element of the CVW, which absorbs part of the hard radiation, is CVD-diamond foil with a diameter of 40 mm and a thickness of 0.3 mm. Between it and the copper flanges $60 \times 10$ with windows $35 \times 8$ mm$^2$ there is a layer of low-melting liquid metal 0.5 mm thick. Water cooling is carried out using mini-channels measuring $0.5 \times 1$ mm$^2$ located inside copper flanges. The lower part of Fig. 1 shows a schematic histogram of heat release (marked in red in the upper figure) from the absorbed part of the synchrotron beam radiation. This histogram of heat release in a foil selected volume from a particular wiggler was calculated by analogy with the available experimental data outside the scope of the work performed, and it is the input data for the presented simulation. In general, heat release depends on the parameters of hard radiation and its dimensions, the material that absorbs the radiation, and the geometric parameters of the element (in particular, the thickness). Further, during physical and mathematical modelling, it is the area marked in red in Fig. 1 that is the localized heat source in the CVD-diamond foil. The total heat absorption in the diamond foil is 1290 W.

For the central region of the CVW, temperatures up to 520°C are acceptable, but preferably below 350°C, the cooled periphery can have temperatures up to 150°C, thermal deformations of the diamond foil in the transverse direction (along the y axis) should not exceed 3.0 [3,6-8]. The dimensions of the minichannels are 1.0 mm along the z axis and 0.5 mm along the y axis. The step between minichannels along the z axis is 1 mm. The dimensions of the input and output rectangular tubes are $2.0 \times 2.0$ mm$^2$. Their dimensions were determined from the condition: the cross-sectional area of the inlet/outlet tube is equal to the sum of the cross-sectional areas of the cooling minichannels.

Here and in articles [6-8], physical and mathematical modelling of heat and mass transfer between the synchrotron beamline and a mini-channel cooling system, including all CVW, was carried out. The coupled three-dimensional problem of thermal conductivity and heat transfer was solved: a localized heat source inside the diamond foil (see red in Fig. 1), thermal conductivity throughout the volume of the foil, then thermal conductivity through a thin liquid metal film into the copper flange and through it to the walls of the mini channels. Heat from the mini-channels walls was removed by the water by thermal conductivity and convection, and spread through the water, then carried away with it outside by the flow. In addition, a small part of the heat was dissipated by radiation from the surface of foil, copper and the liquid metal boundaries open into space due to the fact that they were hot in the surrounding space. For example, galistan was taken as a liquid metal, and a product from Diamond Materials [9], with the appropriate characteristics, was taken as a CVD-diamond foil.

In the calculations, the equation of non-stationary thermal conductivity (1) was used; the condition of temperature equality at a contact was used as boundary conditions at the physical boundaries of diamond-galistan, galistan-copper, copper-water. Here $t$ is time, $T$ is temperature, $\alpha$ is the thermal diffusivity coefficient of the material, $n$ is the unit vector of the normal to the boundary. The movement of water was described by non-stationary Navier-Stokes equations (2-3), with the boundary condition for the water velocity on the channel walls - $U$=0. Here: $U = (U_x, U_y, U_z)$ – velocity, $\rho$ – water density, $p$ – pressure, $g$ – gravitational acceleration, $\nu$ – coefficient of kinematic viscosity. At the boundaries of input channels, the temperature and pressure inlet were set equivalent to the input parameters of the water. At the boundaries of the output channels the ambient temperature (22 °C) and the ambient pressure were set. At the modeling a non-stationary k-omega turbulence model was used in the Fluent package [10,11], the time step was 0.0001-0.02 sec. The tools of this software package are based on solving the Navier–Stokes equations using the control volume method. All used thermophysical property values of materials were taken for the current local temperature in accordance with their tabulated temperature dependencies.

$$\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \Delta)\vec{U} = -\frac{1}{\rho_0}\Delta p + \nu \Delta \vec{U} - \beta T \vec{g}, \qquad \frac{\partial T}{\partial t} + \vec{U} \cdot \Delta T = \alpha \Delta T; \quad div \vec{V} = 0. \tag{1}$$

Radiative heat exchange with the surrounding space was taken into account by applying the Stefan-Boltzmann law. Therefore, in ANSYS Fluent, the emissivity (degree of emissivity of the material) $0 \leq \epsilon \leq 1$ and the ambient temperature were set as boundary conditions on the copper flanges and the open part of the diamond foil [8]. In this case, $\epsilon$, depending on the temperature, is equal to: for polished copper – 0.018-0.023, for diamond glass – 0.91-0.94,

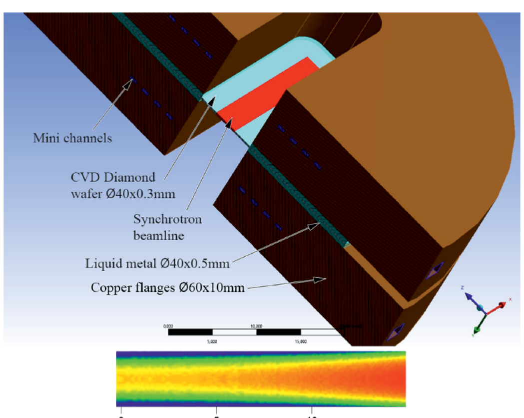


Figure 1: Geometric schematics for CVW, a cross section. Heat flux distribution from synchrotron beamline, schematically, synchrotron beam is $30 \times 3$ mm$^2$, 1290 W.

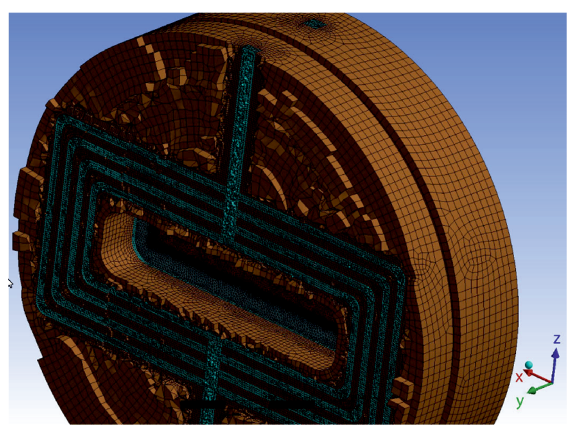


Figure 2: Calculation geometric schematics for CVW, the geometry of the minichannels. A longitudinal section of the flange is shown.

[9,13]. Radiation heat transfer from the open surface of the liquid metal was neglected due to the obvious smallness of its area.

During the simulation, a non-uniform computational grid has been constructed, see Fig. 2, it consists of approximately 5 million elements, with condensation inflation parameter in ANSYS Meshing, [12]) near the channels and in the region of heat release when part of the hard radiation is absorbed. The mesh was generated with condensation in the area of heat generation to more accurately determine local heat fluxes. Thickening parameters: growth rate – 1.2, maximum layers – 5 and transition ratio – 0.27. The quality of the mesh is controlled by the mesh metrics: orthogonal quality – 0.83 and skewness – 0.21. A high orthogonality value means that the mesh faces are perpendicular to the flow, this is necessary for high accuracy of the numerical solution and good convergence. The skewness range for excellent mesh quality should be 0-0.25 according to the documentation of the ANSYS Fluent software package.

Validation of 3-D modelling was controlled in two ways – by bringing together the heat balance and the water balance. For our case, checking the heat balance is a comparison of the values of heat flux through the heated and cold boundaries of the computational domain. At the heated boundary of the computational domain, the magnitude of the heat flux is set with a total power of 1290 W. Heat is removed through the inlet/outlet openings for the cooling water system going to the thermostat, as well as through radiation heat exchange from other surfaces (copper flanges, parts of CVD-diamond foil and the edges of the interlayer from liquid metal). The integral over all surfaces shows the magnitude of the thermal imbalance in the system; it does not exceed $10^{-6}$%. The imbalance of mass water was carried out through control of the cooling water passing through the inlet and outlet openings. The mass imbalance was less than 0.049%.

## 3 Results and discussion

Based on the developed 3D thermal model, this work determined the temperature distribution over the surface of CVD-diamond foil and the dependence of the maximum temperatures in it, on the walls of minichannels and in liquid metal on the flow rate of cooling water in the system. For this purpose, in the calculations, the cooling water pressure from the thermostat into the inlet channels varied from 10.0 to 0.1 atm. The lowest value of pressure studied is 0.1 atm, which corresponds to the situation when the thermostat pump is turned off and water flows through the channels from top to bottom under the influence of gravity only. A regime with a pressure of less than 10 atm may be rational [6]. 3D modelling within the pressure range specified here makes it possible to predict temperature conditions in emergency situations and forced operational changes in the operation of the pumping station.

In particular, the temperature distributions over the CVD-diamond foil surface were determined (Fig. 3) at water flow rates an order of magnitude lower relative to the nominal value. It was found that the maximum temperature in the diamond foil will increase by approximately 32P'B°C, that is, the integrity of the CVD-diamond foil due to possible recrystallization will be determined by the time of lack of proper cooling. Let us clarify this statement. Table 1 presents the results summarizing the calculations performed. The first two columns show the pressure values into the inlet of mini-channels and the realized total water flow rate in them. The third column shows the maximum cooling water velocity in the mini-channels. Next, the values of the maximum temperature $T_{max}$ in: diamond foil, on the minichannel walls and in liquid metal are presented sequentially.

The Tab. 1 shows that when the pressure decreases 100 times (from 10 to 0.1 atm), the

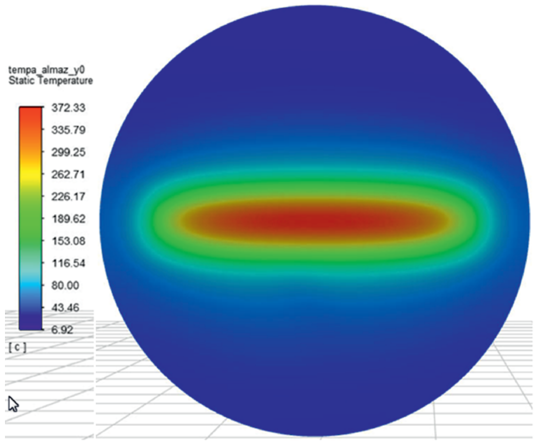


Figure 3: Temperature distribution over the CVD-diamond foil surface in the section $x = 0$, $y = 0$ mm. Foil thickness is 0.3 mm, water flow rate is 1.05 l/min, pressure inlet is 0.1 atm.

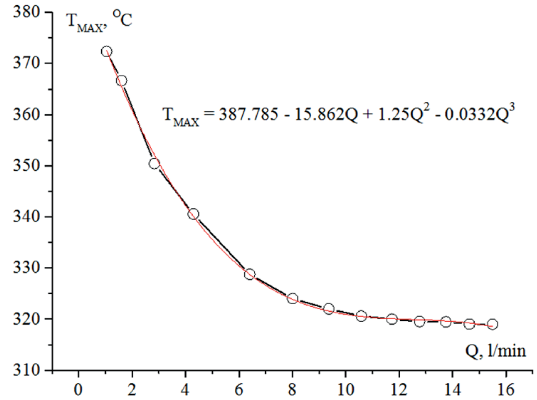


Figure 4: Dependence of the maximum CVD-diamond foil temperature in the coolant flow rate.

Table 1: Effect of water flow rate (inlet pressure) on maximum temperatures of CVW structural elements. CVD-diamond foil thickness is 0.3 mm.

| Inlet pressure, atm | Water flow rate l/min | Maximum cooling water velocity, m/s | CVD-diamond foil Tmax, °C | Minichannel walls Tmax, °C | Liquid metal Tmax, °C |
|---|---|---|---|---|---|
| 10 | 15.49 | 30.47 | 319.0 | 20.1 | 120.3 |
| 9 | 14.63 | 28.77 | 319.7 | 20.7 | 120.8 |
| 8 | 13.66 | 26.91 | 320.4 | 21.3 | 121.3 |
| 7 | 12.76 | 24.96 | 321.6 | 21.8 | 122.0 |
| 6 | 11.74 | 22.95 | 320.5 | 22.2 | 122.0 |
| 5 | 10.59 | 20.76 | 321.6 | 22.9 | 122.0 |
| 4 | 9.37 | 18.34 | 325.7 | 24.7 | 125.1 |
| 3 | 8.01 | 16.50 | 328.3 | 26.3 | 126.5 |
| 2 | 6.40 | 13.28 | 328.8 | 28.2 | 126.5 |
| 1 | 4.30 | 8.18 | 340.5 | 34.0 | 134.9 |
| 0.5 | 2.84 | 5.27 | 350.4 | 40.4 | 141.9 |
| 0.2 | 1.60 | 2.94 | 366.6 | 50.6 | 153.0 |
| 0.1 | 1.05 | 1.93 | 372.3 | 55.4 | 156.8 |

water flow rate will decrease by about 15 times, the maximum temperature on the CVD-diamond foil will rise to 373°C, and the maximum temperature on the mini-channel walls will increase from 20°C to 55.4°C, that is, boiling will not occur in the channels. The dependence of the maximum temperature in CVD-diamond foil on the coolant flow rate is presented in Fig. 4. An analytical approximation of the $T_{max}$ value is also constructed here. Manufacturers (for example, [9]) of CVD-diamond foil indicate maximum temperatures at which processes associated with recrystallization of the foil single crystal, when used in optical devices, can damage it. Being near these boundaries sharply reduces the operating life of the foil as an optical element, which is when the input pressure decreases to 0.5 atm and below. In such cases, an emergency water reservoir must be provided at the pumping station, under a pressure of at least 0.5 atm.

At the same time, the temperature of the liquid metal will change from 120°C to 157°C. This data is important for assessing the liquid metal diffusion into the polycrystalline copper flange and into the diamond foil. Dissolution of liquid metal components in these structures can disrupt their strength properties. However, it is possible to form protective thin-film coatings that reduce the diffusion of liquid metal components [14]. Thus, temperature data in liquid metal are important for the design of CVW elements when choosing rational cooling conditions and changing operating modes of pumping equipment. In particular, it is when types of protective coatings in areas of contact with liquid metal are selected.

## 4 Conclusion

A 3D-modeling of the changes in the temperature field of the most important elements of the wiggler workstation vacuum windows of the Siberian Circular Photon Source SKIF synchrotron was carried out with a decrease in the pressure of cooling water and the window structure water flow rate, up to an emergency stop of the pumping station. It has been established that if the pumps are turned off, the maximum temperature in the diamond foil will rise above 372°C, which can cause recrystallization of the diamond and rupture of the foil. Thus, it is required to have a reserve tank with water under a pressure of at least 0.5 atm. At the same time, boiling will not occur on the minichannel walls. However, the temperature in the liquid metal will increase by 37°C. Without the use of protective coatings, this can significantly increase the diffusion of liquid metal components into the polycrystalline copper flange and diamond foil, which can also lead to rupture of the foil.

## Acknowledgement

The work was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation within the framework of the state assignments by the SKIF Center of the Boreskov Institute of Catalysis SB RAS (FWUR-2024-0040) and by the Kutateladze Institute of Thermophysics SB RAS (project 121031800213-0).

## References

[1] Kabov O., Zubavichus Ya., Cooper K., Pukhovoy M., Vinokurov V., Finnikov K, (2021). *Features of device cooling in wiggler synchrotron workstations*, Journal of Physics: Conference Series, 2057, 012028.

[2] Jaski Y., Cookson D. (2007). *Design and Application of CVD Diamond Windows for X-Rays at the Advanced Photon Source*, AIP Conference Proceedings. 879, 1063.

[3] Schildkamp W., Nikitina, L. (2012). *Manufacturing of diamond windows for synchrotron radiation*, Review of Scientific Instruments, 83(9), 095104.

[4] Wang H., Barg B., Mountford B., McKinlay J., Walsh A. (2015). *A case study of a high heat load equipment at the Australian Synchrotron.*

[5] Benmerrouche M., Sunil C.(2018). *High Energy Engineeering X-ray Scattering (HEX)*, 14th Meeting of the Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF-14).

[6] Pukhovoy M.V., Zolotarev K.V., Vinokurov V.V., Vinokurov V.A., Finnikov K.A., Bykovskaya E.F., Kabov O.A. (2023). *Calculation of cooling systems for CVD-diamond filters of the siberian ring photon source*, Interfacial Phenomena and Heat Transfer, 11(2), 81PIP,вЂњ93.

[7] Pukhovoy M.V., Vinokurov V.V, Vinokurov V.A., Kabov O.A (2023). *Numerical simulation of the diamond window of the synchrotron workstation. Choice of diamond foil thickness (0.2-1.0 mm)*, E3S Web of Conferences, 459, 08010. https://doi.org/10.1051/e3sconf/202345908010

[8] Kabov O., Zubavichus Ya., Cooper K., Pukhovoy M., Vinokurov V., Finnikov K., Ronshin F., Nikitin A., Bykovskaya E., Vinokurov V., Mungalov A., Marchuk, I. (2021). *Device cooling features in wiggler synchrotron workstations*, Journal of Physics: Conference Series, 2119, 012129. https://doi.org/10.1088/1742-6596/2119/1/012129

[9] *Diamond Optical Vacuum Windows*, Diamond Materials GmbH, Freiburg, Germany, 2021. https://www.diamond-materials.com/en/products/optical-windows/uhv-vacuum-windows/

[10] Pastukhov D.F., Volosova N.K., Pastukhov Yu.F. , (2018). *Building non-stationary models in the Ansys Fluent shell*, Polotsk State University (in Russian).

[11] Zienkiewicz O.C., Taylor R.L., Zhu J.Z. (2013) *The Finite Element Method: its Basis and Fundamentals*, (Seventh Edition), Butterworth-Heinemann.

[12] *ANSYS Help.*

[13] Miheev M A, Miheeva I M. (1977). *A short course of heat transfer*, Heat Transfer Basics Energy publishing.

[14] Lyakishev, N.P. (1997).*Phase Diagrams of Binary Metal System*, Metallurgiya, Moscow.

V.V. Vinokurov,
Kutateladze Institute of Thermophysics SB RAS,
pr. Lavrentiev 1, 630090 Novosibirsk, Russia,
Siberian Circular Photon Source "SKIF",
Boreskov Institute of Catalysis SB RAS,
pr. Morskoy 2, 630090 Novosibirsk, Russia,
Email: `jetset.vlad@gmail.com`,

V.A. Vinokurov,
Kutateladze Institute of Thermophysics SB RAS,
pr. Lavrentiev 1, 630090 Novosibirsk, Russia,
Email: `vva.itp.nsc@mail.ru`,

M.V. Pukhovoy,
Kutateladze Institute of Thermophysics SB RAS,
pr. Lavrentiev 1, 630090 Novosibirsk, Russia,
Siberian Circular Photon Source "SKIF",
Boreskov Institute of Catalysis SB RAS,
pr. Morskoy 2, 630090 Novosibirsk, Russia,
Email: `pukhovoy.maxim@yandex.ru`,

O.A. Kabov,
Kutateladze Institute of Thermophysics SB RAS,
pr. Lavrentiev 1, 630090 Novosibirsk, Russia,
Email: `okabov@gmail.com`

Received 08.08.2024, Revised 10.01.2025, Accepted 20.02.2025, Available online 30.06.2025.