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TUNCER M. KUZAY
Advanced Photon Source
Argonne National Laboratory
U.S.A

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Tuncer M. Kuzay
Advance Photon Source
Argonne National Laboratory
Argonne, Illinois 60439
U.S.A

It is well established that Si and SiC have very desirable thermophysical properties (principally thermal conductivity and the thermal expansion) at cryogenic temperatures. This feature makes cryo-cooled optics potentially a good candidate for the first optical crystal of the presently built third generation synchrotron machines with very high heat flux levels. Currently, there is a great deal of interest in such cryo-cooled crystals pursued both experimentally and analytically. The analytical studies involve cut micro or capillary channel crystals. As opposed to the machined channels, porous matrices provide significant advantages⁽¹⁾. They operate very quietly. Such matrices are known to affect superior heat transfer enhancement. Data available in open literature suggest that surface heat flux levels up to $\sim 8 \text{ kW/cm}^2$ are possible. For cryogens for which the boiling heat transfer heat flux is rather a low value in conventional geometries, the enhancement available with such matrices is a very significant characteristic. Cryogens are poor thermal conductors themselves. The fact that at the cryogenic temperatures the Si and/or SiC matrix itself becomes highly conductive, the matrix distributes the surface heat flux into the full volume effectively offsetting the poor conductivity of the coolant. In addition the tortuous path of the coolant through the matrix increases the dwell time for better heat transfer, however, at the expense of increased pressure drop.

In this study, thermal conductivity of such composite matrices and the effective heat transfer coefficient obtainable using them are investigated. A first optics crystal model of Si with Si and/or SiC porous matrix as its heat exchanger and subject to prototypic synchrotron level heat flux is analyzed and limits of the cooling possible with liquid nitrogen in single phase and subcooled boiling heat transfer modes are delineated. ⁽²⁾

(1) T M. Kuzay, " Process of Making Cryogenically Cooled High Thermal Performance Crystal Optics", U.S Patent Applied for, #S69384 July 1990

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INTRODUCTION

The status of the Advanced Photon Source (APS) project at Argonne National Laboratory (ANL) has been described in [1]. A detailed description of the characteristics of the APS machine has been provided in [2]. Due to the high energies involved with these new generation synchrotron machines, and ever increasing demand for higher brilliance, the first optics on the beam line continues to be the prize piece for the current R&D. In the case of the APS Table 1 [3] shows clearly the very high heat flux levels associated with Undulator A and B (580 and 430 W/mm^2 respectively at 24m and on normal incidence) of the current designs. A recent workshop at ANL [4] focused principally on the first optics of a two crystal monochromator which was attended by well over 100 visitors world over. This alone shows the interest and the keen competitive spirit that exists among the world researchers associated with the new generation machines ($6\text{-}8 \text{ GeV}$) to solve the horrendous optics problem of the first crystal.

As this conference amply proves the current research and development (R&D) in synchrotron facilities on the cooling of the high heat load optics seem to be proceeding along use of liquid metals and cryogenics with macro channels; use of water with micro channels ; and, use of innovative crystal geometries (inclined and assymetric crystal geometries) to broaden the beam footprint In this paper, we will focus on a novel method of using highly conductive porous matrices (foams) in conjunction with cryogenic cooling in single phase [5]. The choice for the cryogenic cooling has been mentioned in literature[6]. Basically, the pure silicon crystal manifests an interesting thermal expansion characteristic at cryogenic temperatures . The thermal expansion of the crystal is zero at 110K as well as at a lower temperature of $\sim 30\text{K}$. The former temperature is maintainable economically using a cheap cryogen such as LN_2 . The zero linear expansion coefficient is interesting for the silicon crystals on the APS beam line as this will help minimize the structural distortions in the crystal under thermal loading. Even above and below this mark, the thermal expansion coefficient is still very small. Therefore, if the crystal temperature cannot be maintained uniformly at 110K , the resulting structural distortions will still be small at such temperatures.

Another advantage of the low temperatures in the crystal is such that its thermal conductivity improves very significantly compared to room temperatures (Fig. 2). For example, at 100K, $k = 8.8 \text{ W cm}^{-1} \text{ K}^{-1}$, whereas at 300K, $k = 1.5 \text{ W cm}^{-1} \text{ K}^{-1}$, an improvement almost six folds. This means that the surface or near surface volumetric heating of the crystal under APS radiation will be conducted away rapidly and uniformly and transported to the cryogenic coolant even with relatively thick crystals.

For operational stability and safety it is very desirable that the coolant remains single-phase or in the sub-cooled convective boiling mode.

As for the use of porous matrices, it is evident that the porous matrix offers some unique features. These matrices are readily available in industry today for many desirable crystal/mirror materials including SiC, Be and BeO and others. In this paper we will focus on SiC because of its cheap and ready availability, and its close thermo-mechanical compatibility with single Si crystal. Behaviour of SiC, for example, at LN2 temperatures is very much like that of Si.

Porous matrices can be made with various porosities. At high porosities, the porous matrix behaves like a macro channel crystal. At low porosities it behaves like a micro channel crystal. With no need for elaborate machining, porous matrices bonded to a single crystal Si faceplate in various forms as shown in Fig.1 provide macro or micro channel, cryogenically coolable crystal. In short, a porous matrix is nature's equivalent to man made macro or micro channels. Such a conceptual crystal structure is depicted in Fig.2.

Porous matrices made of Si, SiC, Be, BeO and others are very strong mechanically.

Porous matrices are very quiet in operation. They provide jitter free cooling operation. This is because, the flow in porous media, if turbulent, it is homogeneous with extremely fine turbulence structure. In Darcian and near-Darcian regime it is laminar (more like micro channels).

Porous matrices provide very large extended surfaces internally (more like macro and micro channels, however, usually, an order magnitude higher) and they also provide "tortuosity" to the flow (unlike macro and micro channeling) which lends itself to increased dwell time for the coolant. Subsequently, porous matrices constitute, naturally, superior heat transfer media. In literature, it is quoted that with highly conductive metallic porous

matrices one can remove as much as 7-8 kW/cm² heat flux [6,7, and 8].

Therefore the effective surface heat transfer coefficient of porous matrices can be as large as those attainable with liquid metals and/or the micro channels.

Our own experiments using copper mesh type porous matrices [9] as shown in Fig.4 prove the high heat transfer enhancement available with a porous matrix in a generic APS tube to be used in our high heat load front end components .

FEASIBILITY COMPUTATIONS

From the large amount of literature available on boiling heat transfer in porous media, It is known that the porous matrix heat transfer exhibit a peculiarity that it goes to film boiling from nucleat boiling without going through the critical heat flux [10]. Therefore it is imperative that porous matrix should operate in single phase convective mode or at the most in sub-cooled nucleat boiling region.

Although we propose to use a foam back crystal we will consider here a more conventional silicon crystal about 10 cm wide 15 cm long with 500 holes of 1 mm in size for our cryogenic cooling feasibility computations. For the APS X-ray source we will consider the one with the largest total load of 10 kW level (APS Undulator A) which also produces the highest heat flux on the first crystal.

First, it may be instructive to calculate the theoretical limits of heat removal by single phase liquid N₂ (LN₂) at various flow rates of, say, 5, 10 and 20 gpm (0.322, 0.65 and 1.29 l/s respectively). Non-boiling is assured by pressurizing the system to the critical point of N₂ which is 126.2K and 3396 x 10⁶ Pa, or, in English units about 492 psi (33.5 atm). Then, the theoretical limit of sensible heat removal by LN₂ introduced to the test section at a subcooled 66K will be approximately as follows:

<u>Flow (gpm)</u>	<u>Q (kW)</u>
5	17.8
10	35.6
20	71.1

If LN₂ is allowed to rise to 110K at a system pressure of 492 psi (33.5 atm, then, there will be substantial sub-cooled boiling contribution to the total heat transfer in addition to the sensible heat removal from 66K to 110K. Now let's return to our problem.

From elementary enthalpy considerations, Table 2 is constructed for the required mass flow rates of N₂ at an inlet temperature of 66K.

For an arbitrary but feasible crystal geometry Table 3 lists the resulting flow and Reynolds number information. Table 4 lists the resulting heat transfer coefficients and the ΔT wall-fluid temperature differences.

If Case #4 above is assumed to be a viable case, the resulting bulk fluid and wall temperatures along a flow channel can be computed to be:

<u>Z (in.)</u>	<u>T_f (K)</u>	<u>T_w (K)</u>
1	71.1	87.7
2	75.9	92.6
4	85.3	102
6	95.3	112
12	124.3	141

T_{sat} to correspond to 5 atm system pressure in Case #4 is 94K. Therefore, the bulk fluid exceeds saturation temperatures within 6 in. length of the crystal and the saturated boiling region is reached which is undesirable.

A popular correlation among many, such as the Bowring correlation [11] on the estimate of the onset of boiling (ONB) point yields the following:

$$(\Delta T_{\text{sat}})_{\text{ONB}} = X P r_f \phi_{\text{ONB}}^{0.5} \quad (1)$$

$$\phi_{\text{ONB}} = h_f \left[(\Delta T_{\text{sat}})_{\text{ONB}} + \Delta T_{\text{SUB}}(2) \right] \quad (2)$$

When the LN₂ flowing through the channels reaches the saturation temperature of 94K to correspond to the applied 5 atm system pressure (DT_{SUB}) = 0. Then, from data for N₂

$$X = 0.00996 [\dot{R} / Btu t^2]^{0.5}$$

$$Pr_f = 2.016$$

$$(\Delta T_{sat})_{ONB} = 0.00996 \times 2.016 \phi_{ONB}^{0.5}$$

$$\phi_{ONB} = 441 (\Delta T_{sat})_{ONB}$$

$$\phi_{ONB} = 78.4 \text{ Btu/hr ft}^2$$

$$(\Delta T_{sat})_{ONB} = 0.179 \dot{R} = 0.1 \text{ K}$$

$$(T_w)_{ONB} = 169.3 \dot{R} = 94.1 \text{ K}$$

Again, using one of the many correlations available in literature on saturated boiling regime, such as the Roshenow correlation [11]

$$\frac{C_{pf} \Delta T_{sat}}{l_{fg}} = C_{sf} \left[\frac{\phi_{SCB}}{\mu_f l_{fg}} \sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}} \right]^{0.33} \left[\frac{C_{pf}}{k_f} \right]^{1.7} \quad (3)$$

for Case #4 one can calculate the following ΔT_{sat} f_{SCB} values (SCB–subcooled boiling)

$\Delta T_{sat} (\text{°F})$	$f_{SCB} (\text{Btu/ft}^2 \text{ hr})$
1	.44
5	58
10	473
40	31543
100	500000

It is apparent that the Roshenow and Bowring correlations yield consistent results, namely, that onset of boiling (ONB) in the crystal channels occurs with negligible increase in the wall temperature above the saturation temperature once the bulk fluid is allowed to reach the saturation temperature at the prevailing system pressure. Then, the vapor generation will be explosive with undesirable results. To eliminate this possibility at the exit of the crystal channels conditions should allow the maintenance of some partial subcooling. This means that the system pressure at exit should be high enough to prevent the fluid bulk temperature from reaching saturation by some margin. It appears that this can be achieved, minimally, by maintaining a 103 psi (7 atm) system pressure ($T_{\text{sat}} = 98\text{K}$) with a 6-inch long crystal subject to 10 kW total load.

The above first cut feasibility study indicates that indeed it is possible to cool a high heat load optics using sub-cooled liquid nitrogen.

FURTHER POROUS MATRIX CONSIDERATIONS

Porous matrices have large internal surfaces. The internal surface area of a porous matrix with volumetric porosity of ϵ is calculated as follows:

Spherical particles:

$$S=6(1-\epsilon)/D_p$$

Wire like particles (wire meshes):

$$S=4(1-\epsilon)/D_p$$

Simple calculations will indicate that internal surface area for heat transfer in porous matrices are enormous and will be dictated by the particle dimension.

The volumetric heat transfer coefficient in porous matrices is approximately given by:

$$Nu \cong C Re Pr^{1/3}$$

Using the Biot number limit of heat transfer one can optimize the pore size for a given material (such as SiC etc) and the coolant (LNE, gallium, water etc).

How well the heat can be transferred from the surface into the matrix of a porous matrix can be simply appreciated by applying finite or infinite fin assumption to a porous matrix element. At both cases the total heat transferred scales with $\propto(hPAk)^{1/2}$. It is seen here that the high conductivity attained by Si, SiC, Be, BeO like materials at cryogenic temperatures is key to this efficient transfer of heat into the body of the matrix despite the poor thermal conductivity of the cryogenic coolants.

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Fig. 1. Representative ways porous matrix can be incorporated in a Si crystal structure

ADVANCED PHOTON SOURCE

Fig. 2. Schematic of a conceptual Si crystal assembly using a porous heat exchanger.

Fig. 3. Heat transfer data with porous copper mesh in tubes

Table 1. Design Parameters of Various APS Insertion Devices for a Ring Energy of 7 GeV and 100 mA Stored Current

	Undulators				Wigglers		Bending
	A	B	C	D	A	B	Magnet
Period length [cm]	3.1	2.1	20.0	8.0	15.0	25.0	NA
Device length [m]	5.00	5.00	5.00	5.00	1.50	5.00	3.06
Number of periods	160	238	25	62	10	20	NA
Max. magnetic field B_0 [T]	0.80	0.40	0.15	1.00	1.00	0.30	0.6
Characteristic energy E_c [keV]	26.0	13.0	4.9	32.6	32.6	9.8	19.5
$1/\gamma$ [mrad]	0.073	0.073	0.073	0.073	0.073	0.073	0.073
Max. deflection parameter, K	2.51	1.03	2.81	8.76	13.96	7.00	NA
K/γ [mrad]	0.183	0.075	0.205	0.639	1.019	0.511	NA
Total power [kW]	10.0	2.5	0.35	15.5	4.6	1.4	0.52*
Peak power [kW/mrad ²]	333	250	9.8	160	26.0	15.6	1.78
Peak power @15 m [kW/mm ²]	1.5	1.1	0.04	0.71	0.12	0.07	0.008
" " @24 m [kW/mm ²]	0.58	0.43	0.02	0.28	0.05	0.03	0.003
" " @30 m [kW/mm ²]	0.37	0.28	0.01	0.18	0.03	0.02	0.002
" " @40 m [kW/mm ²]	0.21	0.16	0.01	0.10	0.02	0.01	0.001

*Assuming 6 mrad horizontal acceptance.

Table 2. Condensed Thermophysical Properties of N₂ in the Cryogenic Range of Interest

T		C _p Btu (lb °F) ⁻¹	η lbm (ft/s) ⁻¹	ρ lbm ft ⁻³	ν ft ² s ⁻¹	k Btu (hr/ft °F)	α ft ² s ⁻¹	Pr
F	K							
-340	65		.184 x 10 ⁻³	53.8	.342 x 10 ⁻⁵	.0925	3.686 x 10 ⁻³	3.43
	66.45	0.4794						
-335	69.23	0.4818						
	70		.146	52.4	.278	.0873	3.461	2.89
-330	72.01	0.4855						
-325	74.67	0.4877						
-320	77.56	0.4899						
	80		0.099	49.3	.202	.0764	3.156	2.30
-315	80.34	0.4922						
-310	83.12	0.4949						
	85		0.085	47.9	.178	.0711	2.989	2.14
-305	88	0.4984						
-300	88.68	0.5028						
	90		0.074	46.5	.159	.0660	2.805	2.04
-295	91.45	0.5085						
-290	94.23	0.5157						
	95		0.065	45	.145	.0608	2.620	2.02

Table 3. Mass Flow Rate

Case	Sat. Pressure (bar)	Sat. Temp. (K)	ΔT_{rise} (K)	$\dot{m}$ (lb/m)	Q (gpm)
1	1	77	11	3549	8.45
2	2	84.5	18.5	2101	5.15
3	3	88	22	1759	4.38
4	5	94	28	1375	3.54
5	7	99	33	1161	3.01
6	10	105	40	951	2.48

Table 4. 500 Hole Crystal (1 mm ϕ Holes) Flow-Reynolds Number Data*

Case	G (lb/hr ft ²)	v (ft/s)	Re
1	8.4×10^5	4.45	5247
2	4.97	2.712	3814
3	4.20	2.31	3757
4	3.25	1.66	3030
5	2.80	1.59	2936
6	2.25	1.31	2597

Total flow surface area ~ 2.54 ft²
 Total flow area ~ 0.6087 in²

Table 5. 500 Hole Geometry, Heat Transfer Coefficients and the Wall-Bulk Fluid Temperature Differences

Case	h (Btu/hr ft ² °F)	ΔT_{w-f} (°F)	T _{bulk} (K)	T _{wall} (K)
1	885	15.2	77	85.4
2	611	22	84.5	96.7
3	571	23.5	88	101
4	441	30.5	94	110
5	406	33.1	99	117.4