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Thermal Analysis on Heat Absorption for X04SFE Photon Shutter

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Abstract

Cooling of thermal load induced by synchrotron radiation is a mayor challenge for beam defining elements and photon shutters and other front-end elements. Here we verified a simple tube model with Fluid Structure Interactions FSI calculations[2] using the existing photon shutter in the front-end of the X04S (MS) beamline.
The model was implemented in a Python script, which allows easy adaptions for other configurations in future development of front-end components. This script is freely available[3] to use under the GNU general public license.
We showed that the model used represents in good approximation the results from the much more complex FSI calculations. However, the model assumes uniform power load, which is typically not the case for synchrotron radiation. The limitations of the model have been investigated and suitable methods and tolerances to adapt for this limitation are presented.

Boundary Conditions

Table 1

Parameter given by the SLS setup		
Water inlet temperature	25 °C	
Power by Undulator	3.9 kW	
Max. power density P'_{max}	20.9 kW/rad^2	Results in: 10.5 W/mm^2 (3 ° tilt)
Systemic limits to be met		
Maximal cooling water velocity	2.5..3 m/s	At 4 m/s cavities build up, <1.5 m/s ideal in terms of vibrations
Maximal pressure difference (in-out)	4 bar	
Maximum power density for copper	20..70 W/mm^2	20 W/mm^2 for CU-OFE, 50 W/mm^2 for CuCr1Zr, 70 W/mm^2 for Glidcop
Maximum inner wall temperature	100 °C	
Used constants		
Density water ρ_{water}	997.05 kg/m^3	
Thermal capacity water Cp_{water}	4179 J/(kg*K)	
Thermal conductivity water λ_{water}	0.598 W(m*K)	
Dynamic viscosity water η_{water}	890.45e-6 kg/(m*s)	
Thermal conductivity copper λ_{Cu}	390 W/(m*K)	

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[2] Siemens NX
[3] https://github.com/Schweif/PSI/blob/master/CoolingTube.py

Simplified Model

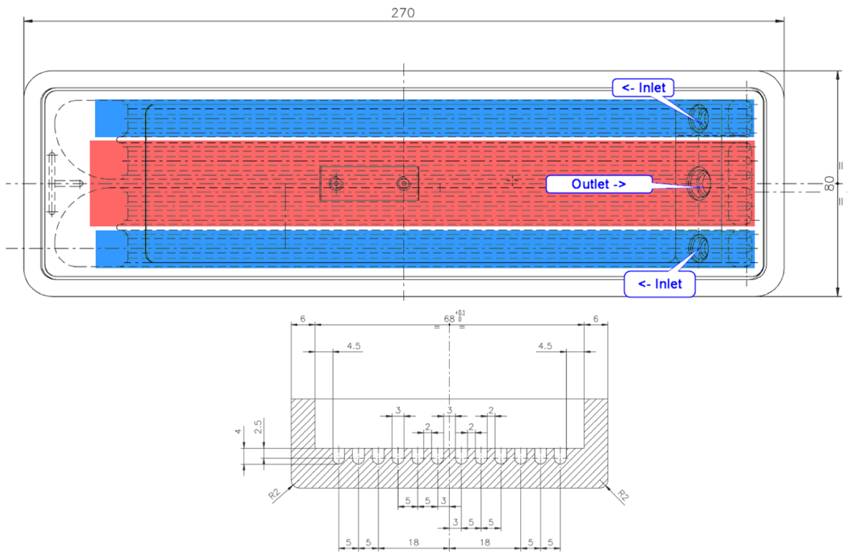

Figure 1: Mechanical setup of the photon shutter at X04S. PSI Planarchiv Nr. 30040.26.021.

The model used reduces the system to a simple tube model. Two different configurations were calculated and compared to FSI calculations.
In a first approach, all the individual grooves were assumed to be in series. This model has shown to be too simple and not feasible. The mayor disadvantage of this model is that the narrow groves build up very high fluid velocities within the single channel. With the given limitations for the velocity, this ultimately results in high temperature differences of the fluid in- and outlet.
The following assumptions have been made for this model (see Table 2):

Table 2

No of individual tubes	1
Tube diameter	3.5 mm
Length of an individual tube	12 * 220 mm
Power incident area (WxL)	68 mm x 220 mm
Thickness of the wall	7 mm

A much better approach showed to be dividing the system into six individual tubes in a parallel configuration. In addition, this model does much better represent the configuration of the actual photon shutter.
The following assumptions have been made in order to verify this model with the existing photon shutter at the X04S beamline (see Table 3):

Table 3

No of individual tubes in parallel	6
Tube diameter	3 mm
Length of an individual tube	2 * 220 mm
Power incident area (WxL)	68 mm x 220 mm
Thickness of the wall	7 mm

Power absorbed by one tube	P0 / 6 = 4 kW / 6 = 666.6 W
Volume flux low per tube	Total flux / 6
Total pressure difference	Pressure difference per tube * 6
Temperature differences will remain the same for the individual tubes and for the whole system	
The incident power is uniformly distributed over the area below the tubes	
All fluid parameter e.g. heat transfer coefficient remain constant for each of the six tubes	

Calculations Single Tube:

```
Delta T (35 °C) is given, volume flow will be calculated
Flow needed is:                            1.6 l/min
Velocity omega is:                         2.9 m/s
Velocity is ok
The Reynolds Number Re is:                 11172.5
Flow conditions is mixed turbulent; Nu will be calculated after Wagner 3.78
Nusselt Number Nu is: Nu =                 84.9
The heat transfer coefficient Alpha is:    14502.8 W/(m**2*K)
The average wall temperature is            52.0 °C
The inner outlet wall temperature is       69.5 °C
The inlet wall temperature is              34.5 °C
Darcy friction factor calculated after Blasius
The pressure loss in the tube is           0.9 bar
The outside wall temperature is            74.3 °C
```

Side notes on this calculation

Configurations from Table 2 used. In this calculation delta T (the difference in temperature between inlet and outlet) has been varied in order to meet the specifications given in the Boundary Conditions section.

Calculations Six Parallel Tubes:

```
Volume flow (6 l/min) is given, delta T will be calculated
Delta T needed is:                         9.6 K
Velocity omega is:                         2.4 m/s
Velocity is ok
Prandt Number Pr is:                       6.2
Prand Number ideal
The Reynolds Number Re is:                 7920.4
Flow conditions is mixed turbulent; Nu will be calculated after Wagner 3.78
Nusselt Number Nu is: Nu =                 61.3
The heat transfer coefficient Alpha is:    12225.7 W/(m**2*K)
The average wall temperature is            42.9 °C
The inner outlet wall temperature is       47.7 °C
The inlet wall temperature is              38.1 °C
Darcy friction factor calculated after Blasius
The pressure loss in the tube is           0.0 bar
The outside wall temperature is            52.5 °C
```

Side notes on this calculation

Configurations from Table 3 and Parameter Set A used. In this calculation the volume flow of the liquid has been given. It is the same volume flow as it is set to the actual photon shutter installed at X04SFE.

Comparison with Fluid Structure Interactions Calculations

Table 4

Value	6 Parallel Tubes	FSI
Delta T fluid [K]	9.6	9.5
Heat transfer coefficient Alpha [W/(m²*K)]	12'2225	12'000...13'000
Max. wall temperature water side [°C]	47.7	40
Max. wall temp. vacuum side [°C]	52.5	45
Delta T solid (vacuum / fluid) [°C]	4.8	5
Parameter Set	A	

The fluid temperature difference between the inlet and outlet temperature is about the same for both methods. This is not surprising since for the forced convection the temperature difference is solely defined through the volume current and the thermal capacity of the fluid.

The heat transfer coefficient of the simplified model is in perfect agreement with the FSI model. The FSI calculation varies the heat transfer coefficient a long with the mechanical setup whereas in the Python script it is kept constant.

The wall temperatures are about 8 °C higher with the 6 Parallel Tubes model than with the FSI calculations. This is due to the fact, that the FSI element not only considers the straight grooves of the water channel, as it is done by the Python script, but also the grooves at the watershed and the in- and outlet nozzles. By prolonging the tubes 6 cm each (approximately the channel length added by the watershed and the in- and outlet nozzles, Parameter Set B) the same wall temperatures are reached.

Calculations with Power Gradient According to Undulator Radiation

Using the SPECTRA[4] software the power density of the undulator (U14) of the X04S beamline has been simulated. The resulting profile was then adapted for the tilting of the photon shutter and used as the power input profile for the FSI analysis.

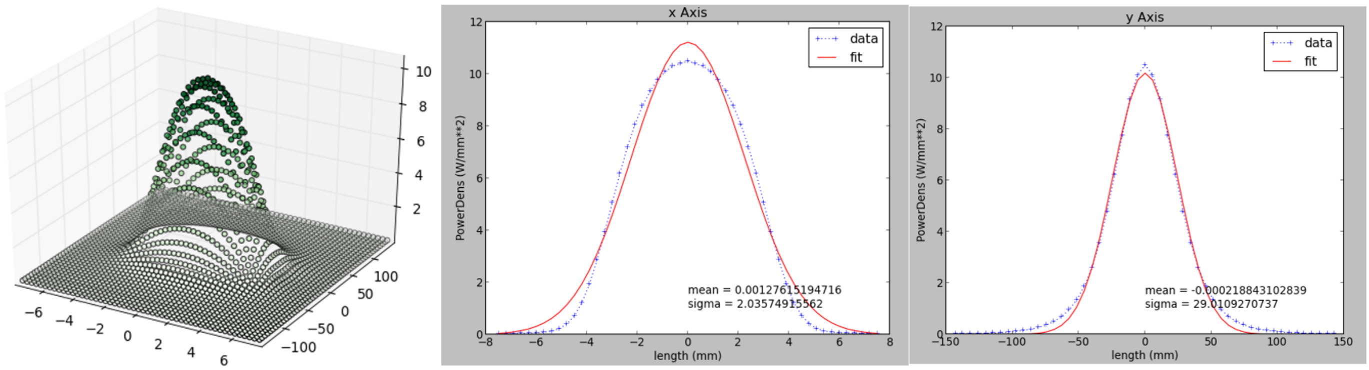

Figure 2: Power density distribution of the U14 undulator at the surface of the tilted (3 °) photon shutter.

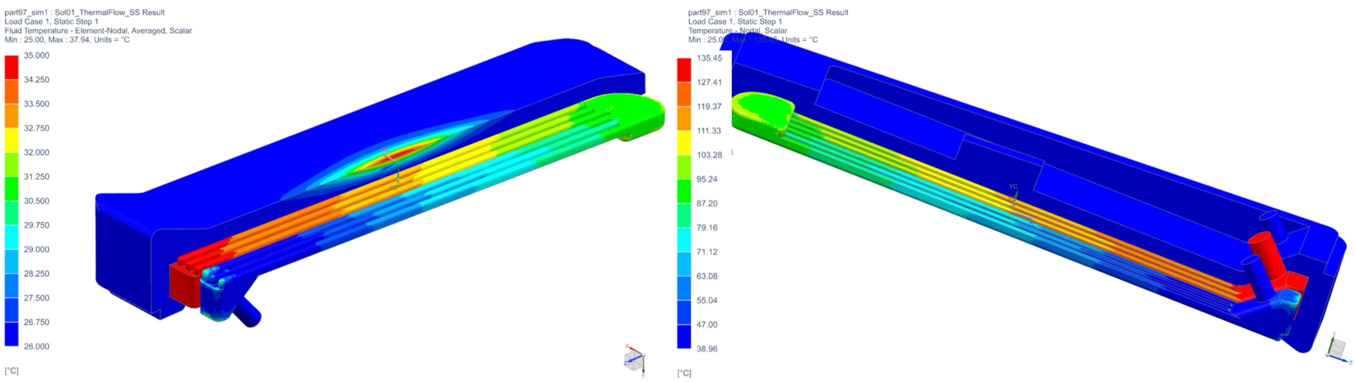

Figure 3: Results of the FSI analysis with power density from ID simulations. Left color scale temperatures of the water, right color scale temperatures of the solid.

Table 5

Value	FSI	Reduced Surface
Delta T fluid [K]	9.5	9.6
Heat transfer coefficient Alpha [W/(m^2*K)]	10’000	12’2225
Max. wall temperature water side [°C]	38	48
Max. wall temp. vacuum side [°C]	135	3xσ = 165, 4xσ = 114
Parameter Set		C

[4] SPECTRA by T. Tanaka: http://spectrax.org/spectra/

When performing the FSI analysis using the calculated power density form the undulator simulations the results inside the water channel remain more or less the same.
This is well understood, since the total power deposited on the photon shutter remains the same and the fluid dynamics are dominated by the geometry.
However, the temperature on the solid is locally increased due to the inhomogeneous power load.

This behavior can be modeled in the Python script as follows:

- The fluid dynamic parameters are kept and remain the same as for the Six Parallel Tubes model (i.e. Parameter Set B)
- Reduction of the area for the heat exchange between the fluid and the solid.

Note that in the used model this area reduction only affects the heat exchange inside the solid. For the fluid equally distributed heat transfer from the solid to the liquid is assumed since the surface of the fluid channel remains the same.
The reduction of the area for heat exchange has been calculated for and area of 3σ and 4σ of the ID profile on the surface of the photon shutter (Parameter Set C and Table 5). The resulting temperatures were 165 °C and 116 °C respectively. The value form the FSI analysis is 135 °C and lies in between the two values.

Conclusion

The Python script using only a simple tube model corresponds with relatively good accuracy to the much more sophisticated Fluid Structure Interactions analysis and can therefore be used for the design and concepts of water-cooled components. In the case of synchrotron radiation where the power is introduced by a relatively sharp Gaussian peak, we suggest to reduce the area of the heat transfer to 3σ. This should leave some tolerance for the maximum temperature of the wall.
In the case where tolerances are thigh and material or system limits are nearly met, we recommend to perform a FSI analysis for verification.

Appendix

All calculations were performed with commit dvc0dd4[5]. The influence of thermal radiation has been neglected for both the FSI analysis and the model used in the Python script.

Parameter Set A:

```
#Constants Water
roh_water = 997.05 # kg/m**3 density at 25 °C
Cp_water = 4179.0 #J/(kg*K) thermal capacity
lambda_water = 0.598 #W/(m*K) thermal conductivity
nue_water = 890.45e-6 #kg/(m*s) dynamic viscosity at 25 °C

#Constants Solid
lambda_solid = 390 #W/(m*K) thermal conductivity of the wall material CuCr1Zr= 320, Glidcop =365, Cu =390
W/8m*K)
epsylon_solid = 0.6 #w/o unit, emission number e.g. Cu polished = 0.04, Cu oxidized = 0.6, black colored
0.9
thickness = 0.007 #m thickness of the material between fluid and power in
width = 0.068 #4*0.00235 #m width on which the power is applied
length = 0.220 #4*0.02901 #m width on which the power is applied

#Boundary conditions if 0 it will be calculated, set according to machine
P0= 4000 #J/s = W heating power
d= 0.003 #m diameter of water tube
l= 2*0.220 #m length of water tube in series e.g. if you have two parallel tube with a length l each enter
l
n= 6 # number of tubes (with the same diameter) in parallel configuration flowing in the same direction
T_i = 25 #°C water inlet temperature

#choose which parameter should be calculated (set to False if it should be calculated)
delta_T = False # K difference between inlet and outlet temperature, set to False to calculate delta T
v_flow_l_n = 6 #Volume flow  of the water in l/min through all parallel tubes, set to False to calculate
volume current in l/min
model= 'Wagner' #Select a calculation model. Available models are:
```

Parameter Set B:

```
#Constants Water
roh_water = 997.05 # kg/m**3 density at 25 °C
Cp_water = 4179.0 #J/(kg*K) thermal capacity
lambda_water = 0.598 #W/(m*K) thermal conductivity
nue_water = 890.45e-6 #kg/(m*s) dynamic viscosity at 25 °C

#Constants Solid
lambda_solid = 390 #W/(m*K) thermal conductivity of the wall material CuCr1Zr= 320, Glidcop =365, Cu =390
W/8m*K)
epsylon_solid = 0.6 #w/o unit, emission number e.g. Cu polished = 0.04, Cu oxidized = 0.6, black colored
0.9
thickness = 0.007 #m thickness of the material between fluid and power in
width = 0.068 #4*0.00235 #m width on which the power is applied
length = 0.28#4*0.02901 #m width on which the power is applied

#Boundary conditions if 0 it will be calculated, set according to machine
P0= 4000 #J/s = W heating power
d= 0.003 #m diameter of water tube
l= 2*0.28 #m length of water tube in series e.g. if you have two parallel tube with a length l each enter l
n= 6 # number of tubes (with the same diameter) in parallel configuration flowing in the same direction
T_i = 25 #°C water inlet temperature

#choose which parameter should be calculated (set to False if it should be calculated)
delta_T = False # K difference between inlet and outlet temperature, set to False to calculate delta T
```

[5] https://github.com/Schweif/PSI/commit/bdc0dd4b8fc25ee9e9464264d5181d4f634430d1

```
v_flow_l_n = 6 #Volume flow  of the water in l/min through all parallel tubes, set to False to calculate volume current in l/min
model= 'Wagner' #Select a calculation model. Available models are:
```

Parameter Set C:

```
#Constants Water
roh_water = 997.05 # kg/m**3 density at 25 °C
Cp_water = 4179.0 #J/(kg*K) thermal capacity
lambda_water = 0.598 #W/(m*K) thermal conductivity
nue_water = 890.45e-6 #kg/(m*s) dynamic viscosity at 25 °C

#Constants Solid
lambda_solid = 390 #W/(m*K) thermal conductivity of the wall material CuCr1Zr= 320, Glidcop =365, Cu =390 W/8m*K)
epsylon_solid = 0.6 #w/o unit, emission number e.g. Cu polished = 0.04, Cu oxidized = 0.6, black colored 0.9
thickness = 0.007 #m thickness of the material between fluid and power in
width = 4*0.00235 #m width on which the power is applied
length = 4*0.02901 #m width on which the power is applied

#Boundary conditions if 0 it will be calculated, set according to machine
P0= 4000 #J/s = W heating power
d= 0.003 #m diameter of water tube
l= 2*0.22 #m length of water tube in series e.g. if you have two parallel tube with a length l each enter l
n= 6 # number of tubes (with the same diameter) in parallel configuration flowing in the same direction
T_i = 25 #°C water inlet temperature

#choose which parameter should be calculated (set to False if it should be calculated)
delta_T = False # K difference between inlet and outlet temperature, set to False to calculate delta T
v_flow_l_n = 6 #Volume flow  of the water in l/min through all parallel tubes, set to False to calculate volume current in l/min
model= 'Wagner' #Select a calculation model. Available models are:
```