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Design Analyses with XRAP for PETRA/HASYLAB Beamline Filters/Windows

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ABSTRACT

The first synchrotron radiation beamline using a 4-m-long undulator at the 12 GeV storage ring PETRA delivers hard x-ray photons usable up to 300 keV. In order to reduce the low energy photon flux and the related thermal load on the beamline optics, graphite, beryllium, aluminum, copper, and iron filters or windows are installed. With a planned upgrade of the undulator, a deflection parameter of $K = 2.59$ will be reached. The total radiated power of the undulator will then reach (with closed gap) about 15 kW. The central power density will be about 107 W/mrad². Therefore, the design of the filters and windows which interact directly with the white beam becomes a very challenging engineering problem.

The heat transfer and thermal stress analyses of PETRA filters and windows are presented. Different filter or window thicknesses, sizes, at different deflection parameters of the undulator, are discussed. Improved filter or window designs are proposed.

Keywords: x-ray, filter, window, thermal analysis, stress analysis

1. INTRODUCTION

An undulator has been recently installed at a straight section of the PETRA storage ring.¹ This is a 3.3-cm-period device with 121 periods that provides high brilliance x-ray radiation in the 20 - 300 keV energy range.² The maximum central power density of the beam can reach about 107 W/mrad², after an upgrade of the undulator to a smaller gap of 11 mm. This corresponds to a thermal load of 1 kW/mm² at a distance of 100 m from the source.

Figure 1 shows an overview of the undulator beamline at PETRA.³ Figure 2 shows the filter/window position in this beamline. The white beam is split into two in front of the experimental area by a single-crystal monochromator. The main components that have to cope with the thermal load of the white beam are a carbon foil monitor, a shutter and slit system, different windows, monochromator crystals, and finally the beam stop of the white beam. These components are installed at distances more than 100 m from the source point. This distance reduces the power density, but the installed devices have to cope with the total possible beam power of about 15 kW in the maximum. To reduce the incident power on a single component, filters are inserted into the white beam. They reduce the transmitted power to a level that allows safe operation of the downstream device. Windows are also filters and have the additional feature of separating beamline parts with different vacuum pressures. Filters and windows are critical to the safe operation of the beamline.

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All these components would not survive white beam operation without filtering. The difficulty is to choose the right filter. Filters have to meet following criteria:⁴ sufficient transmission of photons, and absorption of a reasonable amount of power to protect the downstream component. The limit of the power absorption of the filter is given by its maximum temperature, etc.

The thermal and thermal stress analyses of PETRA filters and windows for the initial design, as well as results of several improved design options with different filter/window thicknesses, sizes, and different undulator deflection parameters, are presented and compared. The paper will first present the analysis results on an initial design of the PETRA undulator filters. The analysis results of several improved designs are then discussed.

The X-Ray Absorption Package (XRAP)⁵ is a computer code developed for analysis of optical elements in synchrotron radiation facilities. It can generate bending magnet (BM) and insertion device (ID) spectra and calculate their absorption in optical elements including filters, windows, and mirrors. XRAP can directly perform thermal and thermal stress analyses of filters and windows with consideration of radiative cooling and temperature-dependent material properties, such as thermal conductivity, thermal expansion coefficient, and Young's modulus. It can also perform buckling and postbuckling analysis of filter and window structures. XRAP was used to carry out a series of analyses of the PETRA undulator beamline filters and windows with different sizes, thicknesses, and combinations. Finite element analysis is also carried out for the purpose of comparison with XRAP. In the calculations the filters and windows are assumed to be clamped at their edges, and the edges are kept at a temperature of 300 K.

2. ANALYSES OF PETRA UNDULATOR BEAMLINE FILTERS/WINDOWS INITIAL DESIGN

Heat transfer and thermal stress analysis are performed by XRAP for three different deflection parameters, i.e., $K=1.51$, $K=1.81$, and $K=2.59$. The parameters used are: ring energy-12 GeV, ring current-60 mA, period length-3.3 cm, and total periods-121. The K parameter of 2.59 is only reachable after an upgrade of the undulator vacuum chamber.

The materials of the filters that interact with the beam are characterized by a rising Z from the source to the experiment. This helps select the right amount of absorbed power. The first filter is a 1 mm graphite filter followed by a 0.13 mm graphite beam position monitor foil. These filters reduce the thermal load on the following Be window (1 mm thick) and the diamond monochromator crystal of the low energy branch monochromator (see Figure 2). One 5-mm-thick aluminum window and one 1-mm-thick copper window separate the two monochromators (low energy branch and high energy branch). The Al window reduces the thermal load of the Cu window. Both filters have to reduce the absorbed power on the 2-mm-thick silicon monochromator crystal to less than 200 W. The monochromatic beam then leaves the monochromator vacuum system through a noncooled 0.5 mm steel window. In the analysis, the silicon crystal is treated as a filter.

The material properties used are listed in table 1. For thermal stress analysis, only elastic analyses are performed. In practice, once the maximum stress surpasses the yielding point, the maximum stress will be relaxed through plastic deformation. When in the plastic range, low cycle fatigue of the material should be a concern.

Table 1. Material properties.

Material	Poisson ratio	Young's Mod. (GPa)	Thermal Cond. (W/cmK)	Thermal Expan. Coef. (1/K)
Graphite	0.2	10	3.5 (1.3 @1900K)	1.2E-6
Be	0.05	303	2.0 (0.4 @1600K)	12.0E-6
Al	0.33	69	1.9	23.0E-6
Cu	0.36	108	3.9	17.0E-6
Si	0.23	167	1.6	2.3E-6
Fe	0.265	197	0.17	11.3E-6

Tables 2 to 4 give the absorbed power, maximum temperature increment in the filter/window from the clamp edge temperature, maximum thermal stresses in horizontal and vertical directions, and shear stress. In the calculations, the first graphite filter is 0.13 mm and is used as beam monitor. The last window is not on the beamline. It is used for the deflected beam only. For the purpose of comparison, it is analyzed as a downstream window.

Table 2. Results for deflection parameter K=1.51.

Filter	Filter Size (mm X mm)	Absorbed Power (W)	Max Temp. Increment (K)	Max Stress σ_x (MPa)	Max Stress σ_y (MPa)	Max Stress τ_{xy} (MPa)
0.13 mm C	51 X 50	47	161	1.54	1.57	0.27
1 mm C	20 X 85	142	42	0.39	0.44	0.11
1 mm Be	15 X 80	58	34	91.29	89.88	22.32
5 mm Al	22 X 30	1979	392	494.67	530.90	113.78
(5 mm Al	15 X 30	1979	273	366.94	391.99	95.47)*
1 mm Cu	15 X 65	1259	466	765.59	764.85	193.35
2 mm Si		43	21	6.46	6.13	1.57
0.5 mm Fe		121	1436	2657.07	2504.23	653.15

* Assumed to be 15 mm in height, rather than 22 mm.

Table 3. Results for deflection parameter K=1.81.

Filter	Filter Size (mm X mm)	Absorbed Power (W)	Max Temp. Increment (K)	Max Stress σ_x (MPa)	Max Stress σ_y (MPa)	Max Stress τ_{xy} (MPa)
0.13 mm C	51 X 50	63	219	2.07	2.13	0.36
1 mm C	20 X 85	193	58	0.54	0.60	0.15
1 mm Be	15 X 80	82	47	128.96	124.45	31.25
5 mm Al	22 X 30	2543	470	611.18	640.02	140.19
(5 mm Al	15 X 30	2543	321	447.47	463.85	115.04)*
1 mm Cu	15 X 65	1770	592	1006.08	984.35	252.87
2 mm Si		69	30	9.76	9.08	2.36
0.5 mm Fe		187	1687	3250.42	2991.32	793.26

* Assumed to be 15 mm in height, rather than 22 mm.

Table 4. Results for deflection parameter $K=2.59$.

Filter	Filter Size (mm X mm)	Absorbed Power (W)	Max Temp. Increment (K)	Max Stress σ_x (MPa)	Max Stress σ_y (MPa)	Max Stress τ_{xy} (MPa)
0.13 mm C	51 X 50	158	428	3.95	4.42	0.70
1 mm C	20 X 85	341	99	0.93	1.02	0.25
1 mm Be	15 X 80	128	66	189.68	174.61	44.43
5 mm Al	22 X 30	3770	573	873.92	816.53	178.69
(5 mm Al	15 X 30	3770	372	575.91	546.81	138.38*
1 mm Cu	15 X 65	3105	794	1480.46	1366.63	358.54
2 mm Si		121	40	14.14	12.45	3.32
0.5 mm Fe		350	1883	4022.40	3517.49	973.65

* Assumed to be 15 mm in height, rather than 22 mm.

From tables 2 to 4, one can see that the Al and Cu filters are subject to high temperature and high stress. In the best case, the calculated temperature increment of an Al filter is 273 °C from the boundary, under the assumption of a constant thermal conductivity, i.e., 1.9 W/cmK. Therefore the real temperature increment is expected to be higher than 273 °C due to low thermal conductivity at high temperature. Also, there should be an additional temperature increment from the cooling channel to the filter edge. Because the melting temperature of aluminum is about 480 °C, the aluminum filter is close to the melting temperature even in the $K=1.51$ case. The thermal stress in the copper filter is well above its yielding point, which means that the copper filter should finally be replaced due to low cycle fatigue. Because the melting temperature of pure copper is 1082 °C and the maximum temperature increment of copper in the case of $K=2.59$ is 794 °C, the temperature of the copper filter is close to the melting point in the worst case.

For graphite, beryllium, and silicon crystal, the maximum temperature and thermal stress seem not to be a concern if the material properties and boundary conditions are all satisfied.

Figure 3 shows the present design of the Al window that is 5 mm thick and 15 mm high.

3. IMPROVED PETRA COPPER AND ALUMINUM WINDOWS

After upgrading the undulator to $K=2.59$, the aluminum and copper windows are subject to high temperature and high thermal stress. Therefore an improvement of the design is needed. In order to make the window safer, different window sizes and thicknesses are studied here to determine a good solution. Several options are considered.

3.1. Smaller copper and aluminum filter

The first option is to use filters with smaller size, i.e., to reduce the height of the filters. Table 5 lists the analysis results in which both the Al and Cu filters are 5 mm in height. The deflection parameter used is 1.81.

Table 5. Results of smaller copper and aluminum filters (both 5 mm high).

Filter	Absorbed Power (W)	Max Temp. (K)	Max Stress σ_x (MPa)	Max Stress σ_y (MPa)	Max Stress τ_{xy} (MPa)
0.13 mm C	158.21	728.26	3.95	4.41	0.70
1 mm C	340.46	399.12	0.93	1.02	0.25
1 mm Be	128.25	366.32	189.65	174.62	44.44
5 mm Al	2067.61	355.68	111.33	87.26	17.23
1 mm Cu	2109.77	430.26	314.83	246.19	48.60

3.2. Thick aluminum filter

Another option to reduce maximum temperature and thermal stress is to use a thicker filter². Table 6 gives the results when the aluminum filter is 10 mm in thickness.

Table 6. The results of an aluminum filter 10 mm thick.

Filter	Absorbed Power (W)	Max Temp. (K)	Max Stress σ_x (MPa)	Max Stress σ_y (MPa)	Max Stress τ_{xy} (MPa)
0.13 mm C	158.21	519.22	2.07	2.13	0.36
1 mm C	340.46	358.35	0.54	0.60	0.15
1 mm Be	128.25	346.94	128.95	124.45	31.26
10 mm Al	2067.61	512.92	298.25	305.11	76.22
1 mm Cu	2109.77	374.57	170.11	138.43	27.81

When a 10 mm Al filter is used instead of one that is 5 mm thick, the high energy photons available to users is a concern. Figure 4 gives the spectra after each filter in the central core for the case of a device gap of 14 mm ($K=1.81$).

3.3. A 7-mm-thick Al filter and a 1-mm-thick Cu filter, both 7 mm in height

To leave the x-ray user with more low energy photons, a 7-mm-thick aluminum filter (7 mm in height) is used. The copper filter is also 7 mm in height. The results are listed in table 7. Because we are only interested in the temperature and stress in the aluminum and copper filters, table 7 only gives the results of these filters.

Table 7. Results of a 7-mm-thick Al filter and a 1-mm-thick Cu filter (both 7 mm in height).

Filter	Absorbed Power (W)	Max Temp. (K)	Max Stress σ_x (MPa)	Max Stress σ_y (MPa)	Max Stress τ_{xy} (MPa)
0.13 mm C	158.21				
1 mm C	340.46				
1 mm Be	128.25				
7 mm Al	2452.54	385.70	161.96	131.23	29.70
1 mm Cu	1774.13	500.04	458.34	368.97	83.83

3.4. A 10-mm-thick Al and a 1-mm-thick Cu filter, both 7 mm in height

One can still find that the copper stress may be in the yielding range in case described above (section 3.3). In order to reduce the thermal stress in the copper filter, a 10-mm-thick aluminum filter is considered in this section. The results are in table 8. Because we are only interested in the temperature and stress in the aluminum and copper filters, table 8 only gives the results of these filters.

Table 8. Results of the case of a 10-mm-thick aluminum filter.

Filter	Absorbed Power (W)	Max Temp. (K)	Max Stress σ_x (MPa)	Max Stress σ_y (MPa)	Max Stress τ_{xy} (MPa)
0.13 mm C	158.21				
1 mm C	340.46				
1 mm Be	128.25				
10 mm Al	2913.50	370.54	133.71	108.04	24.42
1 mm Cu	1402.65	458.51	362.75	292.26	65.98

From tables 5 to 8, it can be seen that using thicker filters that are smaller in size can both reduce the maximum temperature and the maximum thermal stress. However, there are tradeoffs. Thick filters can cut off more low energy photons available to the downstream users. Smaller filter sizes will increase the difficulty of operating the beamline when missteering occurs.

4. CONCLUSIONS

For the PETRA undulator beamline filter/window initial design, the aluminum and copper filters can experience high temperature and high thermal stress. This will cause under worst case conditions either melting or low cycle fatigue. There are several improvement options. Generally, smaller filter sizes and/or thicker filters can be used to achieve the goal of safe operation.

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Figure 1. Overview of the undulator beamline at PETRA

- 1 Be - window
- 2 low energy branch monochromator
- 3 beamshutter 4
- 4 Al - Cu filter
- 5 beamshutter 3
- 6 high energy branch monochromator
- 7 Fe - window

Figure 2 Filter/window position in PETRA undulator beamline

Figure 3. Present design of Al window that is 5 mm thick and 15 mm high.

Figure 4. Spectra after each filter for a device gap of 14 mm