# A heat transfer study for beamline components in high-power wiggler and undulator beamlines. Part II. Beryllium windows (invited)

Q. Shen

*School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853*

M. J. Bedzyk

*Cornell High Energy Synchrotron Source (CHESS), and School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853*

M. J. Keeffe

*Cornell High Energy Synchrotron Source (CHESS), Cornell University, Ithaca, New York 14853*

W. Schildkamp

*Section of Biochemistry, Molecular, and Cell Biology, and Cornell High Energy Synchrotron Source, Cornell University, Ithaca, New York 14853*

(Presented on 30 August 1988)

The designs for heat transfer capabilities of beryllium windows and prefilters at Cornell High Energy Synchrotron Source (CHESS) high power wiggler and undulator beamlines are discussed, based on experimental test results and finite element analysis calculations for determining temperature and thermal stress values and distributions.

## INTRODUCTION

High power insertion devices at high-energy synchrotron radiation beamlines have created a special demand for properly designed beryllium windows that can maintain the UHV integrity of the beamline under the heat load and especially the thermal stress produced by the absorbed radiation. To date a linear heat load model for thermal stress considerations has served as the guide line for Cornell High Energy Synchrotron Source (CHESS) beryllium window design.[1,2] Because of its linear nature, this criterion overestimates the problem, and, therefore, a more extensive study is necessary for future beamline development at CHESS.

The power and power density characteristics of the various insertion devices at CHESS is summarized in Table I of Part I of this article.[3] In this Part II of the article we present a heat transfer and thermal stress study on beryllium window designs for the CHESS 123-pole undulator and the new 24-pole permanent magnet wiggler, using a commercially available finite element analysis computer package—ANSYS.[4] Together with a simulated heat load test, we will discuss the power loading limits for these designs and guide lines for future improvements. The beryllium window design for the 24-pole wiggler beamline is shown in Fig. 1. A similar arrangement of the beryllium window assembly was used for the vertical wiggler beamline at the Photon Factory.[5]

## I. HEAT LOAD SIMULATION TEST

To determine the maximum heat load a beryllium window can tolerate, a prototype window assembly was tested and driven to failure with a simulated heat load from an intense electron beam in an electron beam welder machine. The window was 250 $\mu$m thick, and brazed onto a water-cooled (water temperature $\simeq$ 20 °C) copper flange with a $50\times6$-mm$^2$ window opening. The electron beam size was $45\times5$ mm$^2$ and centered on the outside surface of the window. The window flange was attached to a small vacuum chamber which was filled with nitrogen gas at a pressure of $\sim$10 Torr. By monitoring this pressure a failure in the beryllium window could be detected immediately during the test, since the welding chamber was at $\sim2\times10^{-5}$ Torr.

The power of the electron beam was ramped up in 20 W intervals, starting at 100 W. At each power level the power was switched on and off to simulate the thermal cycling which occurs in the beamline. The temperature of the beryllium window was monitored by five thermal couples that were attached to the inside of the beryllium surface and distributed about 2–3 mm apart from one another around the center of the window.

In Fig. 2 we show the measured maximum temperature on the beryllium window as a function of the electron beam power. It approximately follows a straight line. The maximum temperature result from the ANSYS thermal analysis, which is shown as the solid curve in Fig. 2, is in good agreement with the experiment. Three dimensional STIF 70 elements were used in this thermal analysis and a quadrant of

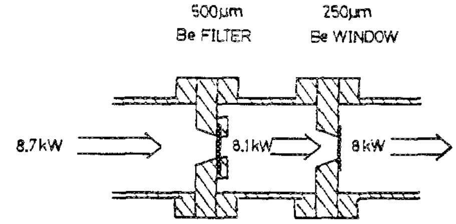


FIG. 1. Cross-sectional side view of the beryllium prefilter/window design for the new 24-pole wiggler beamline. The prefilter is clamped and the window is brazed on the flange. The window in the horizontal direction is about 14 cm long. The power listed corresponds to the 24-pole wiggler at 6 GeV and 100 mA.

 0034-6748/89/071464-04$01.30  

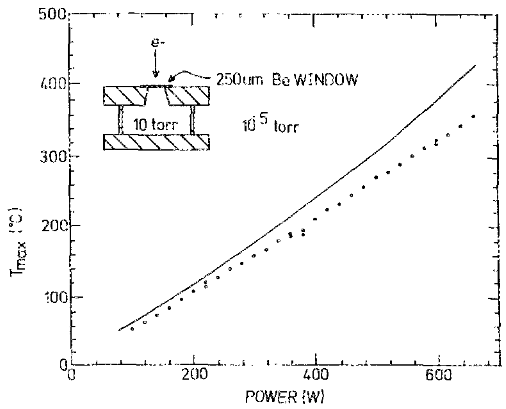


FIG. 2. Maximum temperature on the beryllium window as a function of absorbed power loads. The open circles are the measured maximum temperature during the electron beam simulation test, and the curve is the results from an ANSYS finite element calculation. A schematic of the experimental setup is shown in the insert.

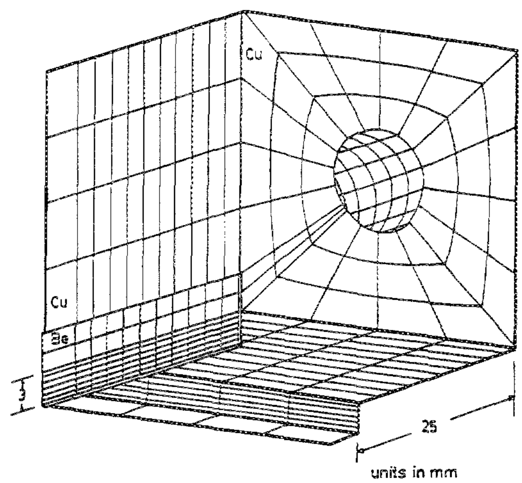


FIG. 3. Quadrant of the ANSYS finite element model for the prototype beryllium window assembly used in the electron beam simulation test. The mesh corresponds to the actual elements used in the calculation. The beryllium foil is two elements thick.

the model is shown in Fig. 3. The convection film coefficient used in the calculation was 1.2 W/cm$^2$/°C and the water temperature was 30 °C . The thermal conductivity for Cu was set to 4.10 W/cm/°C and that for Be was equal to 2.20 W/cm/°C at 0 °C, 1.72 W/cm/°C at 100 °C, 1.34 W/cm/°C at 300 °C and 0.96 W/cm/°C at 700 °C. The temperature dependent thermal conductivity for Be is responsible for the slight nonlinearity of the calculated curve in Fig. 2.

In the test the beryllium window cracked at a power level of 660 W. A thermal stress ANSYS calculation was performed for this power level and a few levels below, using STIF 45 elements and the temperature distribution obtained in the thermal analysis. (We found that a differential pressure of up to 1 atm between the inside and outside window surfaces did not yield any significant increase in the stress distributions.) Two results are obtained from this study: (1) The location of the maximum equivalent stress $\sigma_{max}$ always coincides with the maximum temperature, which is at the center of the beam; but the maximum shear stress component $\sigma_{yz}$ within the cross section of the window and parallel to the electron beam direction is always located at the top edge of the beam. (2) The maximum stress $\sigma_{max}$ is linearly related to the maximum temperature, which can be easily understood by assuming that strains $\epsilon = \delta L / L_0$ are produced by thermal expansion:

$$\epsilon = \sigma_{max}(1-\nu)/E = \alpha(T-T_0).$$

For beryllium, the Young's modulus is $E = 4.2 \times 10^7$ psi ($2.9 \times 10^{11}$ Pascal), the Poisson's ratio is $\nu = 0.07$, and the linear thermal expansion coefficient is $\alpha = 13 \times 10^{-6}$/°C. For a reference temperature $T_0 = 30$ °C, we have

$$\sigma_{max} \text{ (psi)} = 587 \ (T - 30), \tag{1}$$

where $T$ is in degrees Celsius. This simple estimate agrees with the ANSYS calculation.

At 660 W the calculated maximum equivalent stress of 232 kpsi (or 1600 MPa) from ANSYS is about four times greater than the typical yield strength (0.2% offset) $\sigma_{ys} = 50$ kpsi (or 345 MPa) for beryllium given in the literature.[6] In fact, using the failure criterion $\sigma_{max} = \sigma_{ys}$ given in the maximum distortion energy theory,[7] the window should have failed at about 200 W. Another widely used failure theory—maximum shearing stress theory—gives a similar result. We believe that this large discrepancy is due to a much different failure criterion for foil-type materials.

TABLE I. Power absorbed in 125-$\mu$m-thick beryllium layers for the 24-pole wiggler at 6 GeV and 100 mA.

| No. of 125-$\mu$m Be | % Power absorbed | Absorbed power (W) | On axis heat density (W/mm$^3$) |
|---|---|---|---|
| 1 | 3.80 | 334 | 10.63 |
| 2 | 1.36 | 120 | 4.97 |
| 3 | 1.01 | 89 | 3.99 |
| 4 | 0.83 | 73 | 3.48 |
| 5 | 0.72 | 63 | 3.15 |
| 6 | 0.65 | 57 | 2.91 |

## II. BERYLLIUM WINDOW DESIGN FOR THE 24-POLE WIGGLER

The radiated power from the new CHESS 24-pole wiggler is calculated using the PHOTON program.[8] Operated

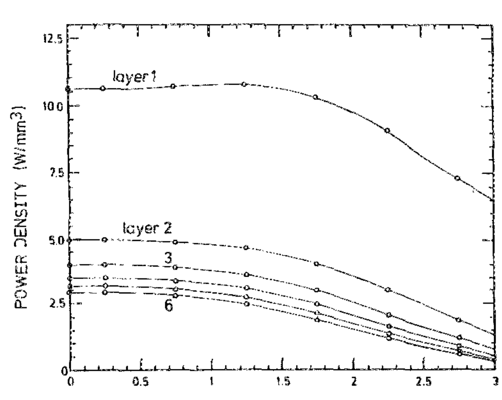


FIG. 4. Calculated vertical distribution of the absorbed power density by a series of successive beryllium windows, each 125 $\mu$m thick, in the 24-pole wiggler beamline, located at about 14.2 m from the source.

TABLE II. ANSYS results of Be window design for the 24-pole wiggler operated at 6 GeV and 100 mA. $f$ = prefilter and $w$ = window.

| Thickness ($\mu$m) | Power abs. (W) | Vertical gap (mm) | Boundary condition | $T_{max}$ (°C) | $\sigma_{max}$ (kpsi) | $\sigma_{max}$ (MPa) |
|---|---|---|---|---|---|---|
| 500 $f$ | 616 | 6.0 | fixed | 216 | 95.0 | 655 |
| 500 $f$ | 616 | 6.0 | 5 kg friction | 216 | 60.4 | 416 |
| 500 $f$ | 616 | 6.0 | free | 216 | 60.3 | 416 |
| 250 $w$ | 120 | 6.0 | fixed | 104 | 36.3 | 250 |
| 250 $w$ | 120 | 7.6 | fixed | 130 | 50.0 | 372 |
| 125 $f$[a] | 110 | 7.6 | free | 80 | 17.1 | 118 |

[a] Prefilter for the 6-pole wiggler at 5.5 GeV and 100 mA.

at 6 GeV, 100 mA, and a critical energy of 30 keV, the total power is 8.8 kW which is spread out in about 3.8 mrad horizontal aperture. For a beryllium window located at 14.2 m from the source, the linear power density on the window is 1.9 kW/cm. Table I shows the absorbed power for each 125-$\mu$m-thick successive Be layer with a vertical height of 7.6 mm.

Figure 4 shows the vertical distribution of the absorbed power density by the beryllium window for the 24-pole wiggler, which was used in the ANSYS calculations. From Fig. 4 one can see that the absorbed power is distributed in a wider vertical region than that corresponding to the critical energy which is 0.9 mm at 14.2 m. This is due to the fact that the power absorbed by beryllium is mainly from the low energy photons which are more spread out than those with the critical energy.

The results from a series of ANSYS calculations are summarized in Table II for a 500-$\mu$m-thick beryllium prefilter followed by a 250-$\mu$m-thick beryllium window. The same material properties described in Sec. II have been used. Both the window and the filter are water cooled in the same way as in Sec. II. Unlike the beryllium window which is brazed into a fixed position, the beryllium prefilter is clamped to the flange. The calculations for the prefilter were done for three types of boundary conditions—free, fixed, and frictional.

Given the fact that the 250-$\mu$m beryllium window in the simulation test breaks at $P_{abs} = 660$ W, $T_{max} = 425$ °C and $\sigma_{max} = 232$ kpsi (1600 MPa), we find that the 500 $\mu$m-filter/250 $\mu$m-window combination should survive the 6 GeV at 200 mA operation for the 24-pole wiggler. This last point will be checked by another simulation test on a free supporting but water-cooled beryllium piece.

Two other useful conclusions can be drawn from this study: (1) For a given power distribution, the maximum temperature on the beryllium window is approximately proportional to the inverse of the vertical gap size of the window. This is also roughly true for the maximum stress. (2) Due to the nonuniform power absorption within the first ~500-$\mu$m thickness of the beryllium material (see Table I), a thicker prefilter will help to increase the thermal conductance but without significantly affecting the heat production and, thus, yield a lower maximum temperature to absorbed power ratio ($T_{max}/P_{abs}$).

TABLE III. Power absorbed in 125-$\mu$m-thick beryllium layers for the undulator at 6 GeV and 100 mA.

| No. of 125-$\mu$m Be | % Power absorbed | Absorbed power (W) | On axis heat density (W/mm$^3$) |
|---|---|---|---|
| 1 | 10.9 | 138 | 43.88 |
| 2 | 3.3 | 42 | 18.00 |
| 3 | 2.3 | 29 | 13.73 |
| 4 | 1.9 | 24 | 11.57 |
| 5 | 1.6 | 20 | 10.14 |
| 6 | 1.3 | 17 | 9.14 |

## III. BERYLLIUM WINDOW DESIGN FOR THE CHESS UNDULATOR

As described in Part I of this article,[3] the total power from the 123-pole permanent magnet undulator is 1150 W at 6 GeV and 100 mA. For a beryllium window located at 16 m from the source, the horizontal beam size is 4.8 mm. The vertical power distribution is again obtained from the PHOTON program. The heat loads for each 125-$\mu$m-thick beryllium layer with a vertical gap size of 7.6 mm are listed in Table III.

It can be seen from Table III that due to the high brightness of the undulator beam, the heat load density is about 4 times greater than that of the 24-pole wiggler although the total power of the undulator is only one-seventh of the wiggler. Because of the highly concentrated power absorption, an ANSYS calculation for the existing 125-$\mu$m-filter/250-$\mu$m-window combination indicates that the maximum temperature on the 125-$\mu$m prefilter can exceed the melting

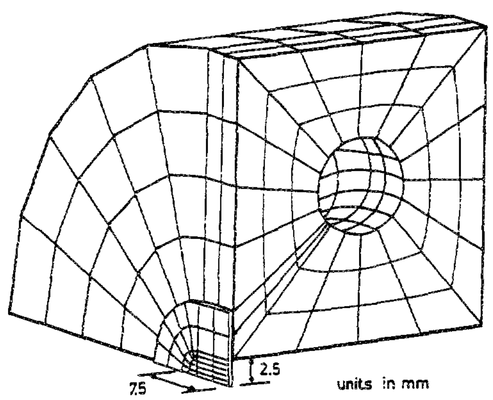


FIG. 5. Quadrant of the ANSYS finite element model for the special beryllium prefilter used in the CHESS undulator run. The mesh corresponds to the actual elements used in the calculation. The beryllium foil is four elements thick.

TABLE IV. ANSYS results of Be window design for CHESS undulator. $f$ = prefilter, 5.4 GeV and 110 mA and $w$ = window, 6.0 GeV and 100 mA.

| Thickness ($\mu$m) | Power abs. (W) | Window size (mm$^2$) | Boundary condition | $T_{max}$ (°C) | $\sigma_{max}$ | |
|---|---|---|---|---|---|---|
| | | | | | (kpsi) | (MPa) |
| 500 $f$ | 210 | 5×15 | free | 396 | 80.2 | 553 |
| 250 $w$ | 37 | 7.6×140 | fixed | 190 | 52.3 | 361 |

temperature (1283 °C) of beryllium at 6 GeV and 80 mA. Therefore, a completely new design for the prefilter was made before the undulator run. During the undulator operation both the new prefilter and the original window have survived a power level corresponding to 5.44 GeV at 110 mA.

The new design for the prefilter is a ~2-cm-thick water-cooled copper gasket with an oval shaped window, 5 mm high and 15 mm wide, on which a 500-$\mu$m-thick beryllium foil is clamped. The model used in the ANSYS calculation is shown in Fig. 5. The results of the thermal and thermal-stress calculations, with identical material properties as listed in Sec. II, are summarized in Table IV.

These maximum stress values, again, are greater than or close to the yield strength values given in Ref. 6 and the fact that these components have survived the operations during the undulator run supports our earlier assessment given at the end of Sec. II.

## IV. CONCLUSIONS

We have found that the simple beryllium prefilter/window design can be highly successful in sharing the heat load and the thermal stress that arise from high-power insertion devices on high-energy storage rings. The following results can serve as a guideline in future designs:

(1) For a given thickness beryllium window which is wide horizontally and narrow vertically in a wiggler-type beamline, the maximum temperature and thermal stress, are roughly proportional to the absorbed total power by the window and inversely proportional to the vertical gap size.

(2) Making the beryllium prefilter thicker causes the maximum temperature to the absorbed power ratio $T_{max}/P_{abs}$ to be lower.

(3) For a beryllium window that is thicker than 250 $\mu$m, the effect of the differential pressure up to 1 atm is negligible, as far as the stresses are concerned.

(4) There are evidences that the criteria in the simple failure theories such as the maximum strain energy theory and the maximum shearing stress theory are not applicable to beryllium foil-type materials.

The last point will be tested experimentally in the near future.

## ACKNOWLEDGMENTS

We would like to thank Jim Sears at Newman Laboratory, Cornell University, for his assistance during the electron beam simulation test. This work was supported by the National Science Foundation under Grant No. DMR-84-12465.

[1] R. Cronin, Stanford Synchrotron Radiation Laboratory (SSRL) Technical Note, 78-TM-01 (1978).
[2] D. H. Bilderback, unpublished note at Cornell High Energy Synchrotron Source (CHESS), 1984.
[3] M. J. Bedzyk, M. J. Keeffe, W. Schildkamp, and Q. Shen, the preceding paper in this issue.
[4] ANSYS Engineering Analysis Systems, Swanson Analysis Systems Inc., Houston, PA 15342.
[5] S. Sato, T. Koide, N. Kanaya, M. Niwano, and I. Nagakura, Nucl. Instrum. Methods A **246**, 177 (1986).
[6] Beryllium Sheet & Plate, Bull. 302 7-PD7, Kawechi Berylco Industries, Inc., Reading, PA 19603.
[7] E. P. Popov, *Mechanics of Materials*, 2nd ed. (Prentice-Hall, Englewood Cliffs, NJ, 1976).
[8] D. Chapman, N. Gmer, N. Lazarz, and W. Thomlinson, Nucl. Instrum. Methods A **266**, 191 (1988).