WHITE-BEAM STOP FOR THE INELASTIC X-RAY SCATTERING BEAMLINE AT THE ADVANCED PHOTON SOURCE

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Abstract

The source for the MERIX instrument at the inelastic x-ray scattering (IXS) beamline at the Advanced Photon Source (APS) will be up to three 2.4-m-long 3.0-cm-period undulators. As a consequence of this long length of undulators, the white beam components see a greatly increased heat load. Although the small size of the exit mask opening (3x1 mm) limits total heat load to acceptable limits, the heat flux is increased significantly over that of the standard a single undulator device commonly used at the APS. The P5 integral shutter white beam stop was one of the components that had to be redesigned due to the increased heat flux. The criteria for the design were the ability to survive the increased heat flux and the ability to be incorporated together with existing designs for the standard P5 modules. The results of number of steady-state and transient cases were investigated using finite element analysis (FEA), and the results are discussed. The new design of the white beam stop based on the results of FEA is presented.

1. Introduction

Two separate inelastic x-ray spectrometers are being built to study collective excitations in condensed matter: medium resolution (MERIX) and high resolution (HERIX). The layout for the inelastic x-ray scattering beamline (IXS-CDT) at the Advanced Photon Source (APS) is shown in Figure 1. The MERIX spectrometer will operate in the 5-12 keV energy range with an energy resolution of ~ 100 meV. Three in-line 2.4-m-long 3.0-cm-period undulators will provide the required photon energy in the first harmonic. This undulator line-up demands increased heat-load handling capability for all front end and beamline components that are exposed to the white beam. This paper presents the design of the new integral shutter capable of withstanding the increased thermal load.

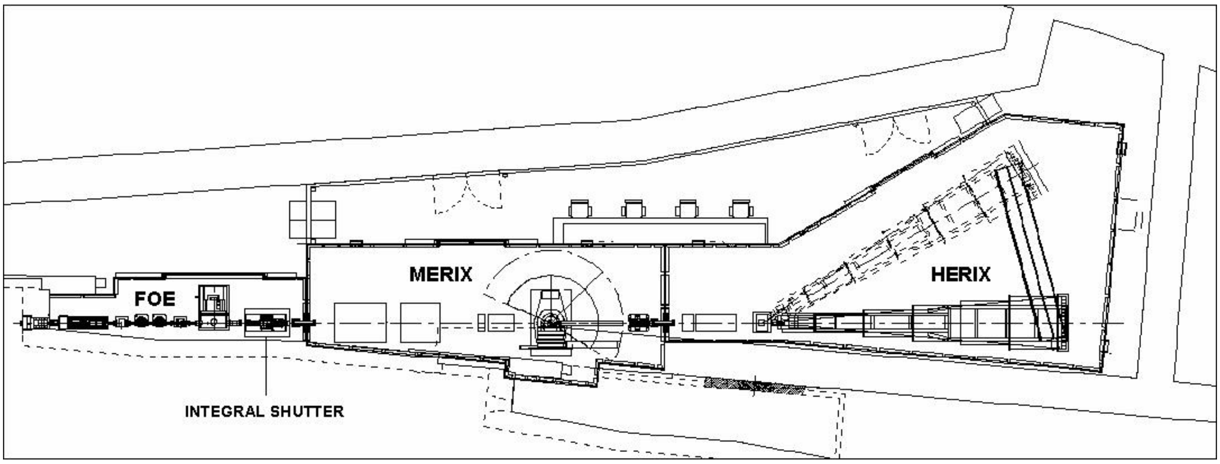


Figure 1: IXS-CDT beamline layout

The standard P5 integral shutter at APS [1], shown in Figure 2, consists of three functional units: a white-beam stop (WBS), a bremsstrahlung stop, and a mono-beam shutter. It was designed to handle white-beam thermal loads of up to 2.5 kW with peak heat fluxes of up to 160 W/mm^2 and mono-beam thermal loads of up to 10 W. The higher heat-load requirements for this beamline necessitated a new WBS design. The ray tracing and calculated thermal power of the monobeam of ~ 0.1 W indicated that the bremsstrahlung stop and mono-beam shutter designs were adequate. Thus, only a new WBS has to be designed that will be capable of handling increased thermal loads and still fit into the existing P5 integral shutter.

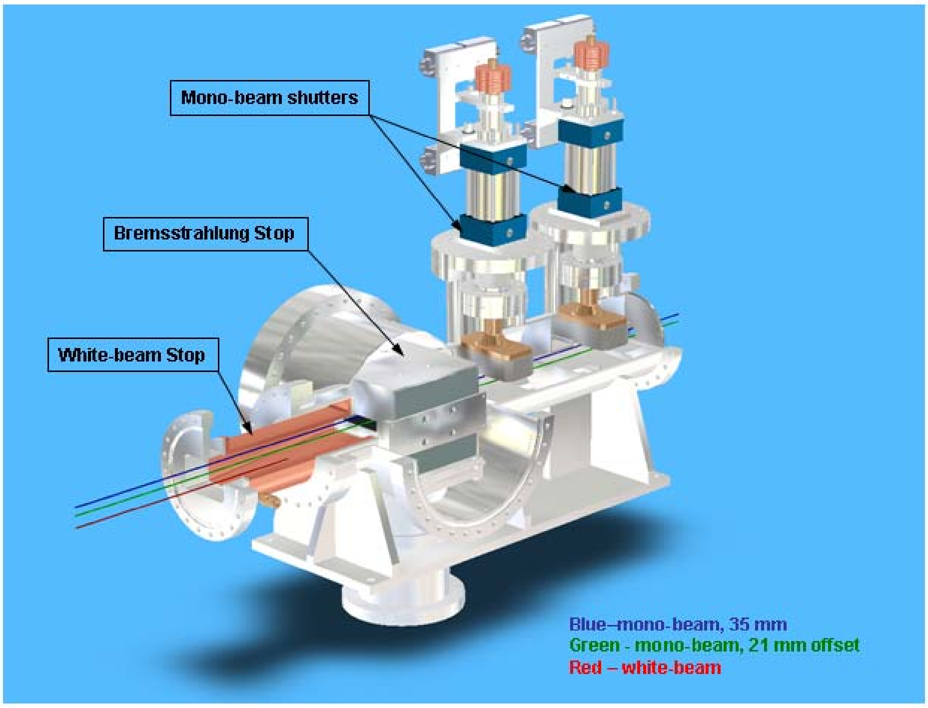


Figure 2: APS standard integral shutter

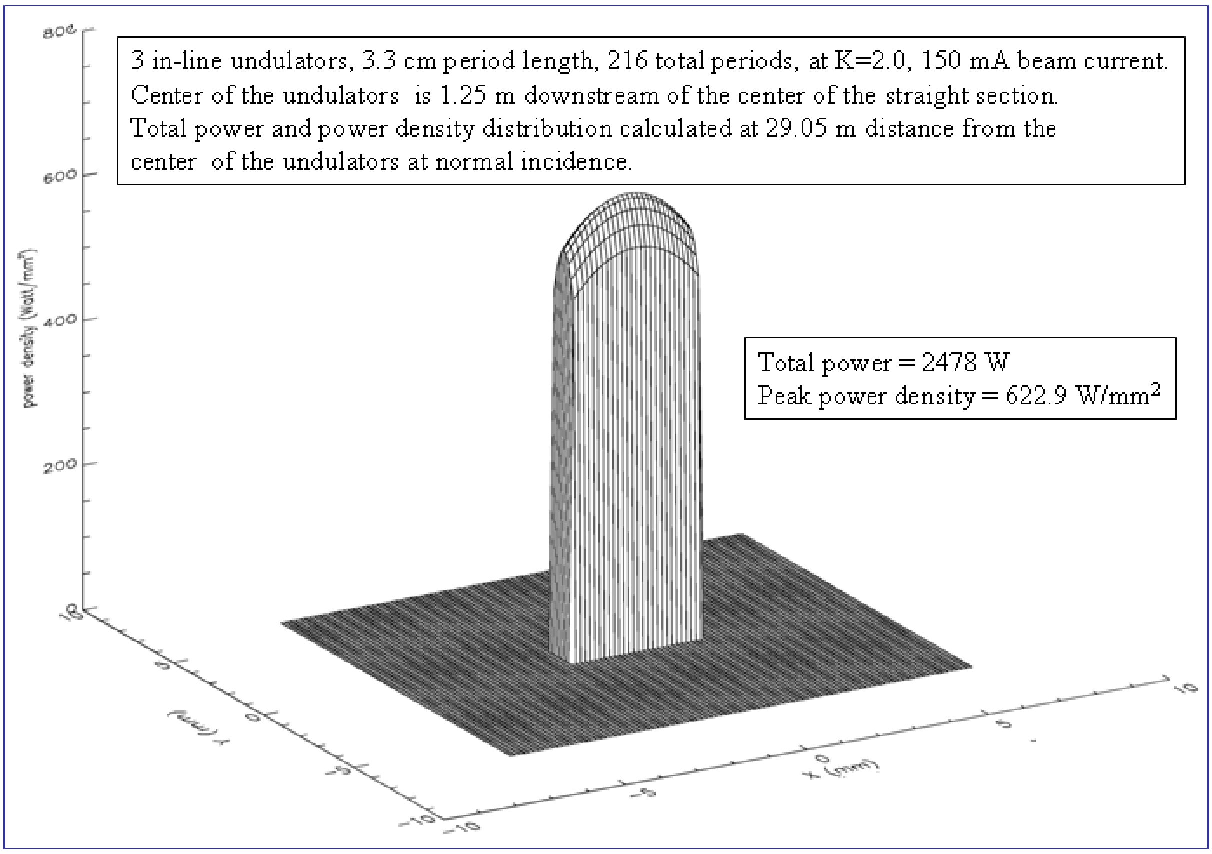
2. Thermal Design of the White-beam Stop

The interaction between the high heat load white-beam and the water-cooled white-beam stop has as a consequence significant increase in the temperature of the white-beam stop. This increase in temperature is accompanied with the emergence of considerable thermally induced stress. Due to the excellent thermal conductivity of Glidcop Al-15 used in fabrication of the white-beam stop body and the efficient cooling [2], both the increase of temperature and stresses are localized. The design criteria established at APS for white-beam stops with a body made from large pieces of Glidcop Al-15 call for stresses to be lower than 300 MPa and for the wall temperature of the cooling channels to be lower than the boiling temperature of water at the channel pressure. In order to restrict the stress levels and the wall temperatures of the cooling channels in the situation where the absorbed thermal power is increased, one can decrease the incidence angle and, if necessary, increase the distance of the cooling channels from the absorbing surface. To design a white-beam stop that will be capable of absorbing the power of the white beam, it is essential to calculate the spatial distribution of the power density of the white beam at the location of the white-beam stop. The calculated spatial distribution of the power density is then projected on the absorbing surface of the white-beam stop, and the temperature and stress distributions are calculated. The design optimization is then performed through variation of the white-beam stop incidence angle and the distance between the cooling channels and absorbing surfaces.

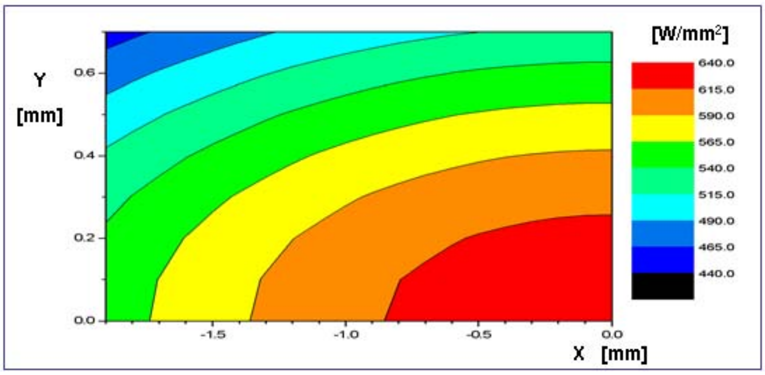
3.1. Calculation of the Spatial Distribution of Power Density

In the synchrotron community, XOP [3] is widely used for undulator power and spectrum calculations. However, the power density output data from XOP is a matrix. To apply the power density results from XOP to a finite element model, curve fitting or data interpolation between the different mesh sizes in XOP and in the finite element analysis (FEA) model must be done, and this process can be time consuming. Fortunately, there is another synchrotron source calculation package available, SRUFF [4], which was developed by Dr. Mati Meron in APS CARS-CAT over the past eight years. It can calculate the spatial distribution of power density of raw power, power absorbed in media, power transmitted through media, and power reflected from mirrors. The output data can be fit into an equation up to a 4^{th}-order Gaussian within SRUFF. The equation is then used in engineering analysis software, such as ANSYS or COSMOS, for thermal analysis. For raw power density calculation, SRUFF is based on the exact analytical expression of angular distribution of undulator power [5], which accounts for an infinite number of harmonics, while XOP integrates the power from the contributing finite number of harmonics. So the results from SRUFF are slightly more conservative compared to those from XOP. The difference of peak power density and total power calculated by SRUFF and by XOP is less than 1%. The power density distribution and total power calculated for the IXS-CDT white-beam stop located at 30.3 m distance and protected by 3x1 mm exit mask located at 25.3 m distance from the center of the straight section are shown in Figure 3. The analytical function describing spatial distribution of power density is:

$$Q_{(x,y)} = 623e^{-0.034322x^2} e^{-0.3992y^2} \quad \text{W/mm}^2.$$



a) Power density calculated with SRUFF



b) Power distribution plot using analytical equation from SRUFF

Figure 3: Power density of the white beam at 30.3 m distance from the center of the straight section

The calculated total power is 2.5 kW and is only slightly higher than in the case of the standard source. This is due to the smaller than usual opening of the IXS-CDT exit mask. But calculated peak heat flux was 625 W/mm^2, four times higher than in the case of the single undulator insertion device.

3.2. Temperature and Thermal Stress Calculations

For the calculation of the temperature and thermally induced stress fields we used the COSMOS Finite Element Analysis package. Calculated x-y distribution of the white-beam power density was projected as the thermal load on the white-beam stop's (Figure 4). The cooling was simulated by applying the

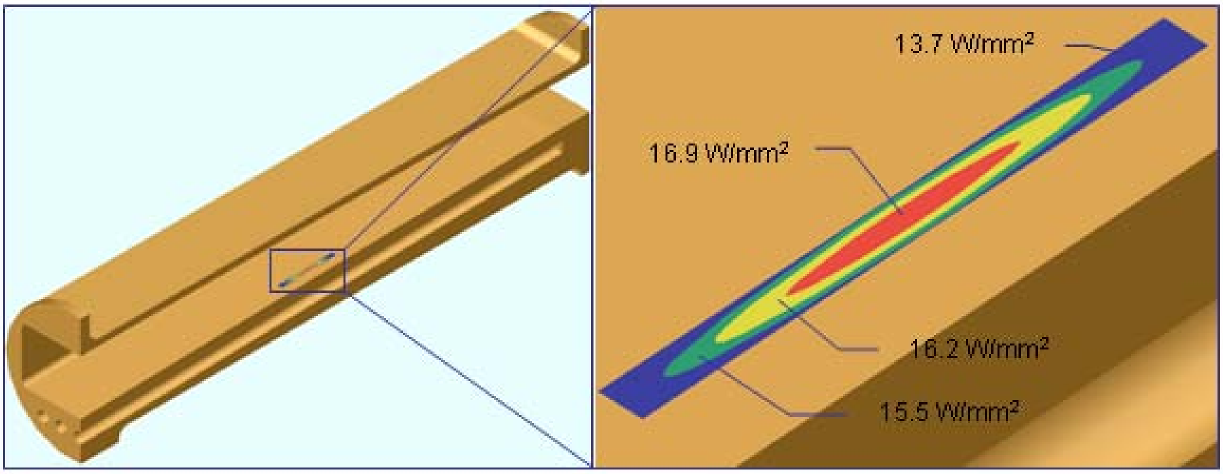


Figure 4: Distribution of the thermal load at the grazing surface of the white-beam stop

coefficient of convective heat transfer h = 15 000 W/m^{2}K [2], to the cooling channel walls. Also, the effect of free convection was simulated by applying the coefficient of convective heat transfer h_{FC} = 8-14 W/m^{2}K to the outer walls of the WBS. For stress calculations, the WBS was fully constrained on one end, and, on the other end the displacement in the y-direction (vertical) was constrained.

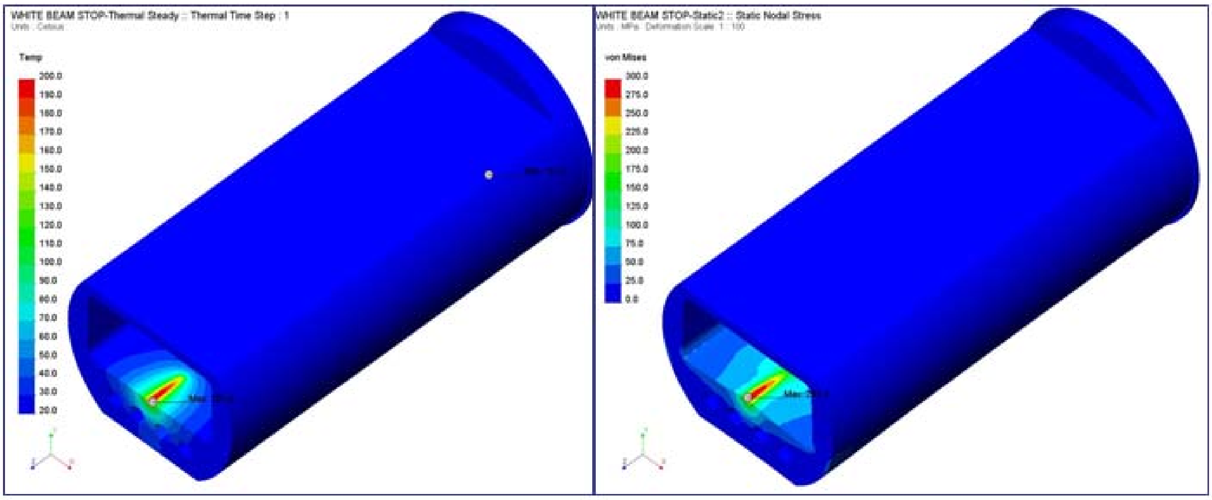


Figure 5: Temperature and stress calculations for normal operation (steady state)

The analysis was performed for a number of grazing angles, and the results are shown in Figure 5. They indicate that the incidence angle of 1.55° ensures that thermal stresses do not exceed 300 MPa (maximum calculated stress value is 291.6 MPa), while the cooling channel wall temperatures are well below the boiling temperature of the water. Also, the analysis of the stress orientation indicated that the material with the highest stress levels is in compression.

The influence of beam misalignment and loss of coolant were investigated through a number of what-if scenarios. Results of the analysis show that beam misalignment up to x = ± 5 mm and y= ±2 mm has a minor effect on both calculated temperature and stress levels. Partial loss of coolant was investigated through the analysis of the loss of coolant in two inner cooling channels. The results of such an analysis show that temperatures reach 235°C, while the stresses reach 315 MPa. Temperatures of the cooling channel walls are still well below the boiling temperature. Although this condition does not lead to the immediate failure, it should be noted that when this happens the most stressed parts of the mask body are exposed to plastic deformation and may in time cause fatigue failure.

Analysis of the total loss of coolant proved that this is a catastrophic event. The results of the transient analysis shows (Figure 6) that, ~ 45 seconds after the total loss of coolant, the temperatures of the cooling channel walls exceed the boiling temperature. At that moment, stresses are in the plastic region (338 MPa) but still lower than the ultimate strength of Glidcop Al-15. The model predicts that the

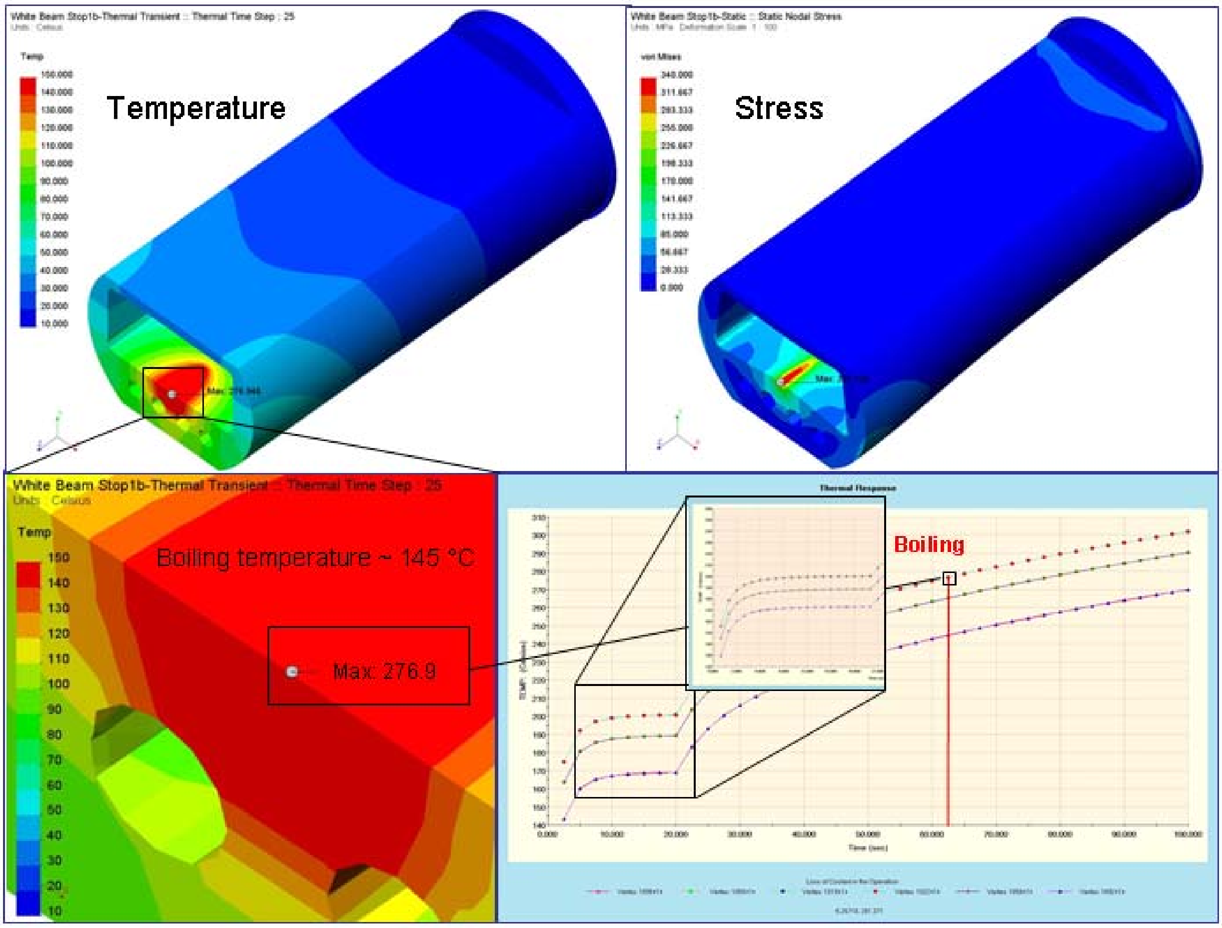


Figure 6: Transient analysis of the total loss of coolant

temperatures and stresses will continue to rise in time, but, due to the boiling, the heat transfer conditions are not accurately described in model and results are not accurate.

3. Mechanical Design of the White-Beam Stop

Once the incidence angle was determined, entrance and exit openings of the WBS body were adjusted to provide masking of the white beam in the case of the beam misalignment. As a consequence of the shallower incidence angle, the overall length of the WBS was increased by 180 mm compared to the original design. Increased length and weight of the mask combined with the shallow incidence angle made the mask very susceptible to misalignment and sagging and an additional adjustable support on the upstream end was added. This support consists of a vertical stage with a micrometer and locking device. The P5 shutter with the new white-beam stop is shown in Figure 7.

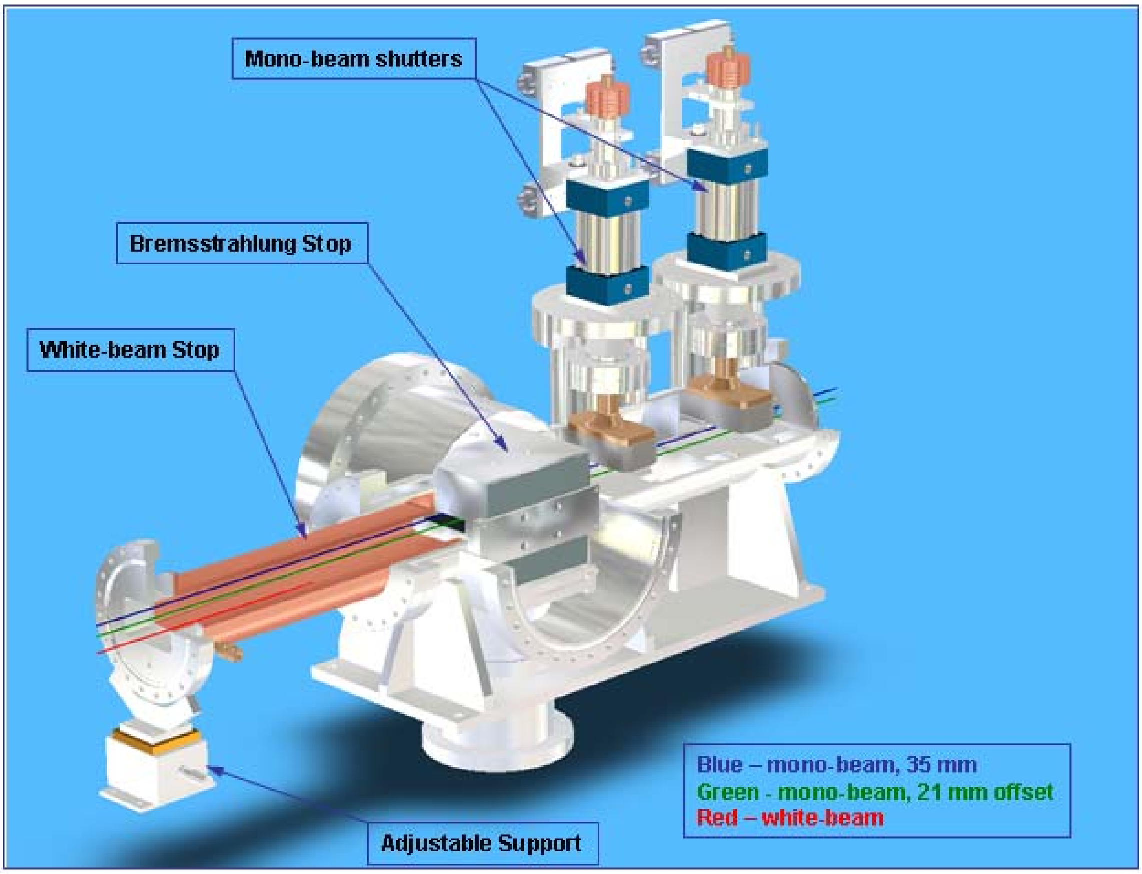


Figure 7: IXS-CDT integral shutter with new white-beam stop

4. Conclusions

The use of three collinear undulators for the IXS-CDT beamline at the APS and higher heat loads that accompany this configuration required a new design for the white-beam mask of the P5 integral shutter. In order to minimize the cost and design time, a new white-beam stop was designed that can withstand the increased heat load of the white beam but can be easily integrated with the existing design of the P5 shutter. The results of the FEA performed for the expected operating conditions and a number of what-if scenarios show that new design will provide reliable operation of the integral shutter. The only condition that can cause catastrophic failure and requires immediate intervention is total loss of coolant.

5. References

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