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DMM THERMAL MECHANICAL DESIGN

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Abstract

A Double Multilayer Monochromator (DMM) was designed in-house for the VMXi beamline. Thermal mechanical finite element analysis was performed to design a novel optic geometry, employing In/Ga eutectic cooling. The integration of a DMM into the existing beamline required additional power management components, such as a low energy power filter, a power detector and compact CuCrZr masks. This paper describes the thermal management challenges and their solutions. The DMM has been fully commissioned and is operational within the original I02 beamline.

INTRODUCTION

The in-situ Versatile Macromolecular Crystallography (VMXi) Beamline is effectively a new beamline which has been built through the original Diamond Phase one beamline I02. The new fully automated endstation has been built downstream of the original within a novel mini-hutch. A new experimental cabin was built to allow I02 operation during the majority of the VMXi build. The insertion device (ID) is planned to be upgraded from a U23 to a Cryo-cooled permanent magnet undulator (CPMU) giving a factor of 3 useful flux increase. The DMM was designed and installed to give an additional 60 fold increase in flux as compared to a Si(111) DCM [1]. The dramatic increase in flux necessitated a detailed evaluation of the power management within the beamline. This paper details the new power management components designed and procured for the VMXi upgrade.

MULTILAYER EUTECTIC COOLING

The DMM was designed to operate over the energy range of 10 – 25 keV using two multilayer stripes 2.0 nm and a 2.4 nm (See Figure 1). The worst case was assumed to be at 12 keV as the ID is optimised for flux at this energy. This is also a larger angle of incidence and hence small foot print. The absorbed power with the future CPMU K2.04, 500mA would be ~ 480W over a 97.5 x 3.4 mm foot print. This flux density would not be challenging for a cryocooled silicon optic; however concerns over the stability of the deposited layer under thermal contraction lead to a water cooled solution. To minimise turbulence induced vibration, a eutectic bath method was chosen. Numerous geometries were investigated using ANSYS but only the chosen one is presented here.

Two eutectic troughs were machined through the top surface of the bounce down first optic. The original aim of separating the cooling channels by slotting the silicon, was to mimic the ESRF mirror cooling model, of side cooling near the optical surface [2]. The troughs also act as temperature stabilised stiffening ribs to the optical surface. When the heatload is not central, which is always the case for the two stripe design a variation of tangential radius across the foot print is introduced but the effect is small enough to be neglected.

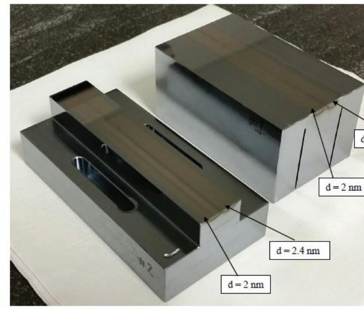

Figure 1: VMXi DMM Multilayer Optics procured from Rigaku, 1st multilayer on the right shown upside-down.

The use of an average young's modulus and poison ratio has been shown to give a good approximation to anisotropic material properties for modelling silicon Zhang [3]; however the non-standard nature of this design may make this finding invalid. The final optimisation was done using the anisotropic material properties. An FEA check was performed see the effect of aligning the X direction with the ML normal and the Y direction normal to the front, side and at ~30º. As expected from the cubic symmetry and Zhang [3], the results are identical for the Y axis aligned with the sides but differ at other angles. The Si(100) surface plane, Si(010) side plane, was found to give the best results and so was used throughout this study.

The eutectic trough was originally designed to come down to within 5 mm of the optical surface; however after manufacturing issues this was increased to 10 mm. This compromised the tangential slope error (fitted parabola radius 50 km to 22 km, 152W absorbed power) but made the optic significantly more robust.

A eutectic wetted area heat transfer coefficient (HTC) of 10,000 W/m^2K was chosen after performing a literature review [4-8]. Prandtl, Nusselt and Reynolds numbers extracted from these sources were used to calculate a range of HTCs. This appears to be a reasonable value for natural convection, which has also been used during the design of other instruments for DLS. The optic tangential slope error was relatively insensitive to HTC i.e. double HTC reduced the deformation by 15%. The eutectic troughs were filled to a depth of ~ 10mm. This was deep enough to ensure that the cooling fins remained immersed over the angular range; while shallow enough to minimise the possibility of splashing upon pump-down. After filling the troughs and inserting the Ni plated Cu fins the water chiller was run with a set-point of 50°C for a few hours. It has been found that this reduces the eutectic viscosity and improves wetting.

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FEA Setup

A bulk fine mesh was defined with a 0.5 mm mesh control applied to the illuminated face and to the bottom faces of the trough isolation cuts (See Figure 2). The illuminated area split faces were used to constrain the model about the centre of the optical area. No support structures were modelled. The calculated heat load profile was projected onto the optic taking care to scale the imported heat flux to give the correct absorbed heat load as measured by a reaction probe on the wetted areas. The models were exported from ProEngineer as a step file with a co-ordinate system defined to match the angle of incidence. The projected heat load imported into ANSYS using an External Data block was then aligned horizontally. A section view through the meshed model is given below.

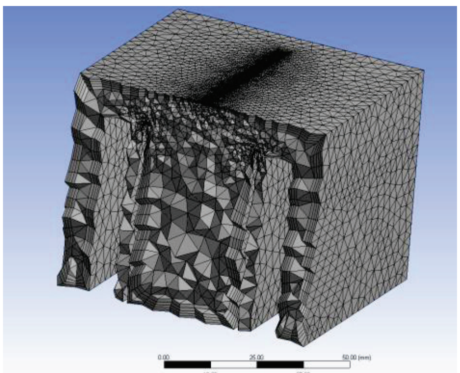

Figure 2: Section view of the meshed multilayer substraight.

FEA Results

It was found that the lower the wetted depth the lower the thermal distortion because the substraight above the wetted area is at the same temperature and hence not distorted.

DLS currently operate with a nominal 300 mA ring current but there are future plans to increase this to 500 mA. The data plots presented below in Figure 3 & 4 are for a CPMU, 500mA 480 W absorbed.

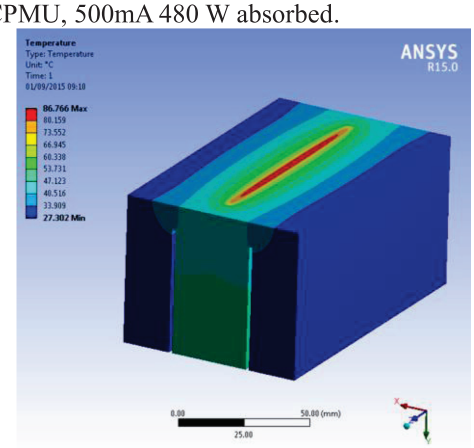

Figure 3: Temperature distribution of the DMM 1st multilayer with an absorbed power of 480W.

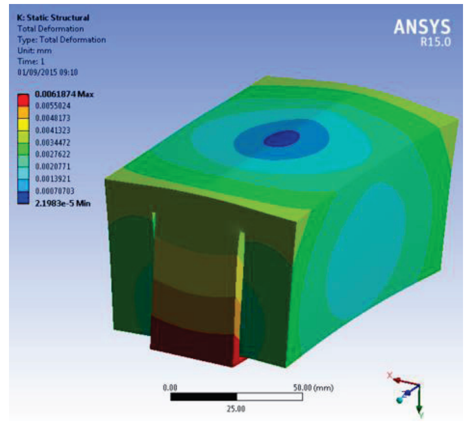

Figure 4: Mechanical Deformation of the DMM 1st multilayer with an absorbed power of 480W.

The FEA study acceptance criteria for the highest foreseeable power load were:

- Eutectic Temperature 34°C (480 W) << 100°C
- Silicon Stress 41 MPa (480 W) << 7 GPa
- Beam collimation effect within compensation range of the KB mirrors – Optics Group Define As Pass

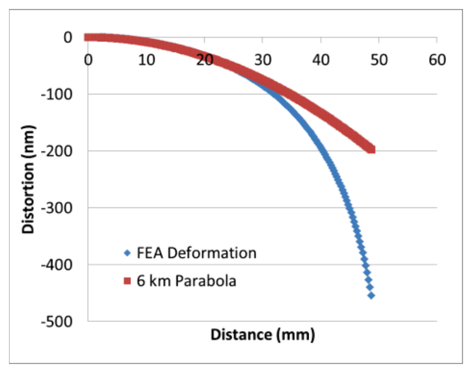

Figure 5: Tangential slope error & 6 km radius parabola plot the DMM 1st multilayer with an absorbed power of 480W. Distortion vs. Distance from spot centre.

The radius reduces to 6 km under the absolute maximum absorbed power condition; however the beamline will not operate with a CPMU with a 500 mA ring current within the next five years if at all (See Figure 5). The optic is deliberately over filled so that only light diffracted from the low slope error central third is accepted into the Endstation.

With Beam DMM Data

No specific tests have been performed to measure the optic slope error; however the DMM has been used to solve structures in diffraction experiments operating with an absorbed heat load of 91 W. The flux at the sample was measured to be 7.8 x10^{13} ph/s, using a calibrated diode. The beam stability was measured at the sample position using an X-ray camera running at 700 Hz. With all the other optics removed from the beam, an X-ray pitch stability of 34 nrads RMS integrated from 1- 350 Hz was measured. This was the best data taken during the day. Sporadic local construction activity clearly had a detrimental effect increasing the stability up to 50 nrads

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RMS. This X-ray camera data was confirmed with a separate single crystal diamond beam position monitor running at 20 kHz.

POWER FILTERS

The DMM delivers a wide band pass monochromated beam at shallow Bragg angles (0.7º – 1.5º, 21 - 9.9 keV for 2.4 nm stripe). The shallow angular range means that the optics also act as mirrors reflecting the low energy harmonics. As DLS is a 3GeV ring the low energy 1st harmonic holds ~ 100W, which would cause unnecessary heating, distortion and damage to downstream components. The low energy harmonics would also corrupt the diffraction data. So the low energy fraction is filtered out by a diamond filter, with the thickness optimised for a specific beamline energy range. The design of a 50 µm thick diamond filter which could absorb 110 W of power over a 3.4 x 2.1 mm spot, indefinitely, is non-trivial. A commercial solution was procured from Diamond Materials GmbH, although the full performance will only be tested when the ID is upgraded. The thin diamond filter is bonded to a thicker diamond support ring, which is in turn bonded to a Cu tube. This provides cooling without over constraining the diamond. An FEA study was performed to validate the design. An elasti-plastic analysis was required as high differential thermal expansion stresses are created. The design requires the annealed Cu to yield to alleviate the stress. Ferrous and titanium alloys have a fatigue endurance limit so a spring may be designed to work for ever; however non-ferrous metals such as Cu do not. The Number of cycles to fracture depend upon numerous factors including composition, grain size and temperature [9]. A “rule of thumb” is that fatigue strength equals 1/3rd the tensile strength [10]. It is difficult to say what the life expectancy of the diamond filters will be, but the total number of temperature cycles in operation will be relatively small. An FEA result is given below in Figure 6.

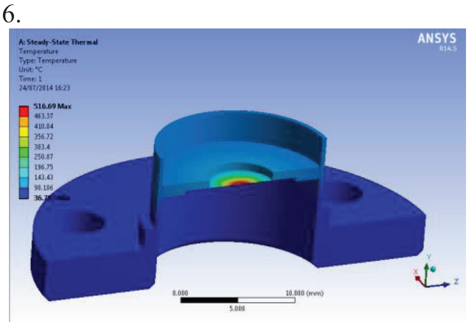

Figure 6: Thermal FEA result for 50 µm diamond filter thickness absorbing 110 W.

POWER DETECTOR

A power detector has been engineered to provide a measurement that the pre-DMM filters are in place and undamaged; while also protecting the detector from the power in case of a failure. The assembly mounted just upstream of the Endstation, employs a 20 µm thick diamond filter with a 100 nm Ti coating to attenuate the visible light and nitrogen doping to give a uniform fluorescence. Downstream of the filter a camera gives a beam position and a diode gives a machine protection signal.

WATER COOLED MASKS

A detailed raytrace was created to identify all the locations down the beamline where significant power might be deposited. The Gas Bremsstrahlung Stop (GBS) and the transfer pipes were clearly vulnerable. Zero length water cooled masks were designed which were thin enough to be inserted between existing components by compressing the bellows (See Figure 7). These masks were machined from CuCrZr alloy removing any requirements for brazing or welding [11]. Prior to installation the knife edge robustness was investigated. No visible damage was caused by repeated bolting and baking cycles as long as the alloy material had been heat treated i.e. using Ampcoloy 972. The photon shutter was also upgraded to a water cooled design.

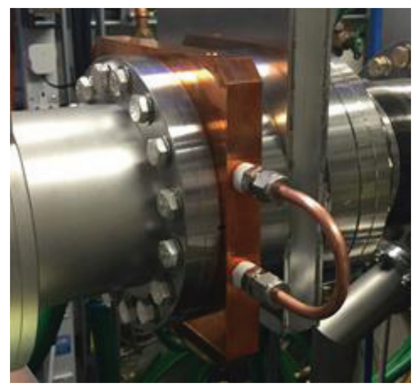

Figure 7: Cu alloy water cooled mask.

Three fixed masks and one moving mask/diamond fluorescent screen were integrated into the DMM design. These masks limit the solid angle of the exiting rays and allow an aperture to either block the deflected, undeflected or both beams. This was required because the VMXi beamline may be operated with either a DCM or DMM. The DMM high power nitrogen doped diamond fluorescent screen was designed with a 10 x 30 mm usable area to allow both the undeflected and 25 mm bounce down monochromated beams to be seen, along with all the alignment steps in between.

CONCLUSION

An in-house designed DMM with power filters and power detector have been built, installed and are operational on the beamline. They have been successfully tested with the existing source and ring current.

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