ANNEALED PYROLITIC GRAPHITE FILTER FOR BEAMLINE 5.0 AT THE ALS

D. Cambie'*, C.Cork, R. Duarte, C. Hopkins, A. Lim, A. Lobodovski, A. MacDowell, S. Marks, H. Padmore, J. Pepper, K. Petermann.

Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
* Xradia, 4570A Sprig Drive, Concord, CA 94520, USA

Abstract

Until recently, an 18 element radiatively cooled graphite foil assembly was used in ALS beamline 5.0 to eliminate the unused low energy x-ray spectrum and therefore reduce the overall power falling on downstream components. This system has worked in the beamline for 6 years, but has been problematic due to severe outgassing during initial use after venting, and the short lifetime of the upstream foils. With the upcoming replacement of the present 37 pole, 2.1 T peak field wiggler, with a 52 pole 1.93 T wiggler, the higher power load dictated that a new design of carbon filter assembly was required. Initial design considerations showed that an optimization of the current foil design would not provide the performance required, and so a new conductively cooled design was adopted, based on a design used at CHESS [1, 2]. This design uses two Annealed Pyrolitic Graphite (APG)[3] foils, 0.2mm thick, each clamped between two water cooled copper frames. APG is a suitable material for this particular application due to its layered structure with very orthotropic thermal properties. In this paper we present the different designs and materials that have been considered and the final design we chose. Clamping, thermal and stress tests have been performed and the results are presented. The same assembly with a slightly different foil thickness has been already installed in beamline 5.0 where the foils absorb a total power of 2600 W. The assembly works as expected. A system comprised of an optical camera and thermocouples have been included in the design to provide diagnostics during operation.

1. Introduction

Beam line 5.0 at the ALS has been operating for 9 years with W16 wiggler, with output at 1.9GeV and 400mA equal to 8400W. A radiatively cooled carbon filter assembly was used to protect the Be window in the frontend [Fig.1]. This filter assembly was expected to absorb 2600 watts (volumetric power load 26.5W/mm3). This assembly consisted of a total of 18 polycrystalline foils, nine 11 micron and nine 17 micron thick for an approximate total effective thickness of 250 micron.
In operation this design had an average lifespan of ~ 2 years (~ 6250 hrs) under ideal conditions. The design was originally estimated to reach temperatures of 1300ºC to 1600ºC which would lead to a considerably longer life than experienced. Estimations of actual temperatures based on the evaporation rate of the foils would require temperatures in the range of 1700ºC to 1900ºC.

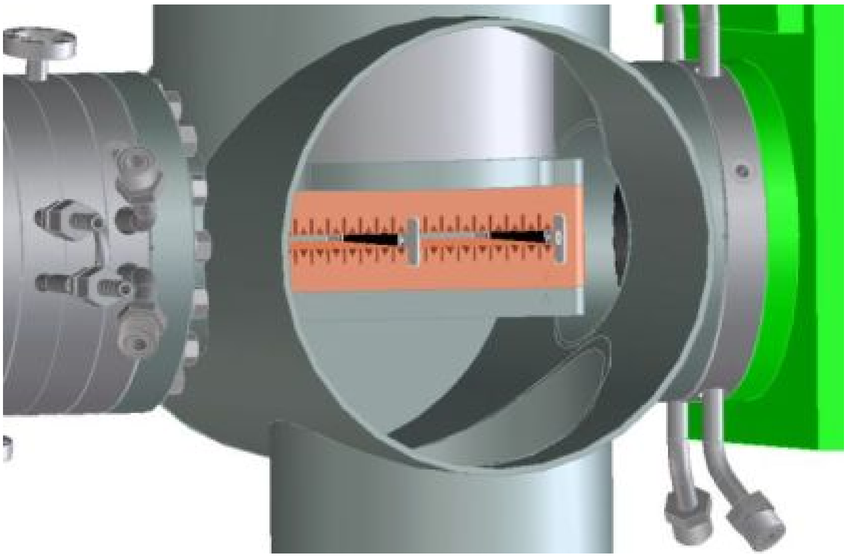

Fig.1: Original Radiatively cooled Design (after updates for improved pumping

With the upgrade of the new W11 wiggler, the carbon filter was expected to absorb ~4000 watts (41 W/mm3 average volumetric power load). Considering the increased power load, the radiatively cooled foils would have a life span of about 2 weeks. Also these polycrystalline foils showed severe outgassing during initial use after venting, requiring extended scrubbing after a shutdown, and their brittle nature made them very susceptible to damage when working in the area.
This required the development of a new directly cooled design. Different materials [table 1] and various means of cooling them have been considered.

Table 1: material properties

Material	***$K_{a,b}$ (W/mK)***	***$K_{thickness}$ (W/mK)***	***$\alpha_{a,b}$ (10^{-6} 1/ºC)***	***α_c (10^{-6} 1/ºC)***
HOPG [4]	*1600*	*8*	*slightly negative*	*20*
APG [3]	*1700*	*10*	*slightly negative*	*25*
PG [4]	*700*	*3.5*	*0.5*	*6.5*
Be	*182*	*182*	*11.7*	*11.7*

2. Filter design

a. Thermal study

The need for very high conductivity lead us to Highly Oriented Pyrolytic Graphite (HOPG) or Annealed Pyrolytic Graphite (APG) which is the trade name of the material that we eventually chose [3]. The conductivity through the thickness for these materials is more than two orders of magnitude smaller than the conductivity in the plane, but is well compensated by the large conduction area and the short distance from the heat sink. Finite Element analyses show that the conduction through the thickness of the HOPG or APG foil is not at all compromised by the poor conductivity in that direction.
The information on the thermal properties for these materials is available at room temperature up to 200 ºC while it is more difficult to find values at higher temperatures, therefore, we used the finite element method only as a comparison tool to decide what material to use and what

method we could use to conduct the heat away. Later, we tested the assembly to detail the final design.

Based on the experience at CHESS [1] we first looked into brazing the foils to cooled frames. The APG has a zero to slightly negative CTE and the process of brazing it to most metals was causing cracks in the foil due to the differential thermal expansion between HOPG and these metals during the cool-down process.

The brazing process also creates much higher stress in the carbon foil than would ever be achieved in operation. For this reason we decided to focus on a contact cooled design that consisted in clamping the foil between two copper cooled frames.

Finite element analysis showed that for the total absorbed power of 4000 W on the area of interest (70mm x 3.5mm) in a 0.4mm thick carbon foil, a face cooling would have been appropriate. We decided to cool both sides of the upper and lower faces of the APG foil to improve the heat transfer and also to prevent possible warping of the carbon foil under high heat loads. The final design is based on the following parameters:

Foil dimensions: 80mm x 20mm x 0.4mm (± 0.1mm)

Beam footprint: 70mm x 3.5mm x 0.4mm (the heat will be applied as volume load [5])

Total heat absorbed: 4000 W for a constant 41W/mm^3 volumetric load.

Convection film coefficient= 15000W/m^{2}K

The resulting temperature profiles from this analysis are shown in Fig.2 through Fig. 4.

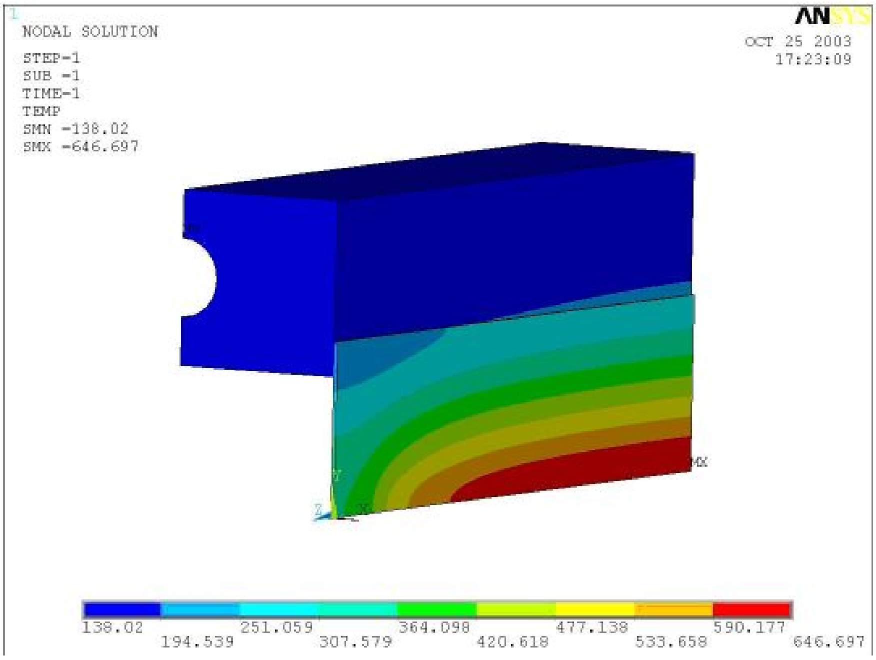

Fig.2: temperature plot on 1/8 symmetry model

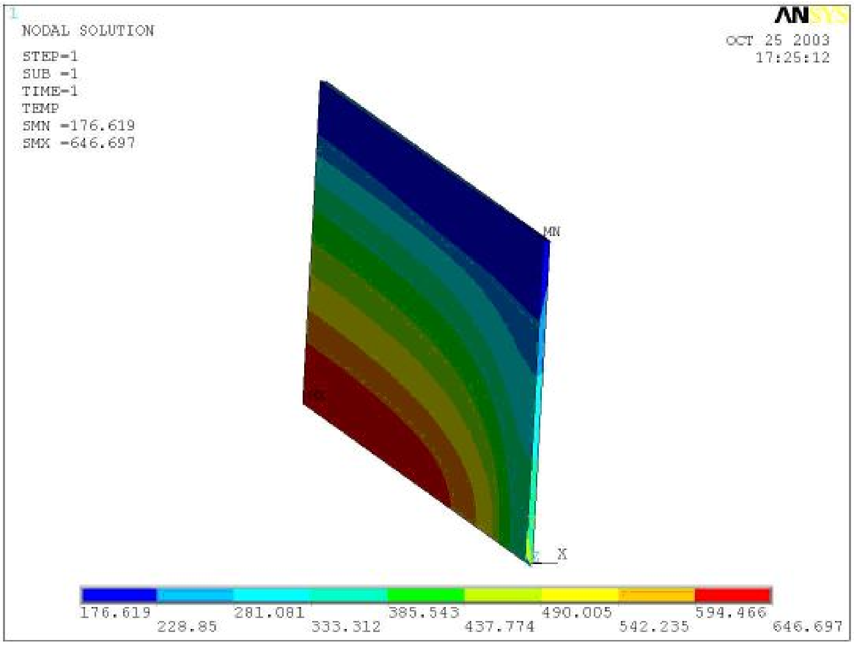

Fig.3: temperature plot on carbon foil

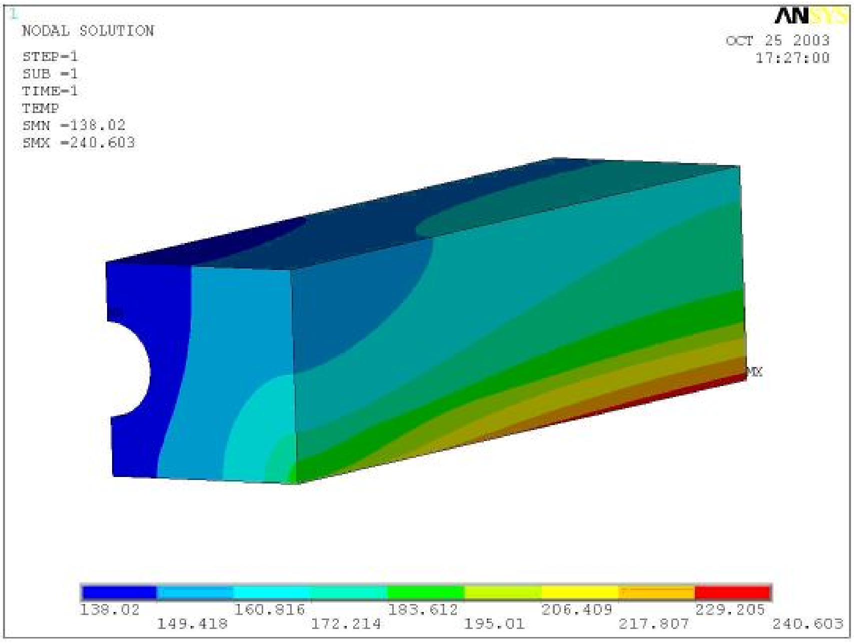

Fig.4: Temperature plot on copper cooled frame

The final design is shown in the following pictures [Fig.5 and Fig.6]. The APG foil is clamped between two water cooled copper frames. A stainless steel pusher is used to make sure that contact is applied in the areas of interest.

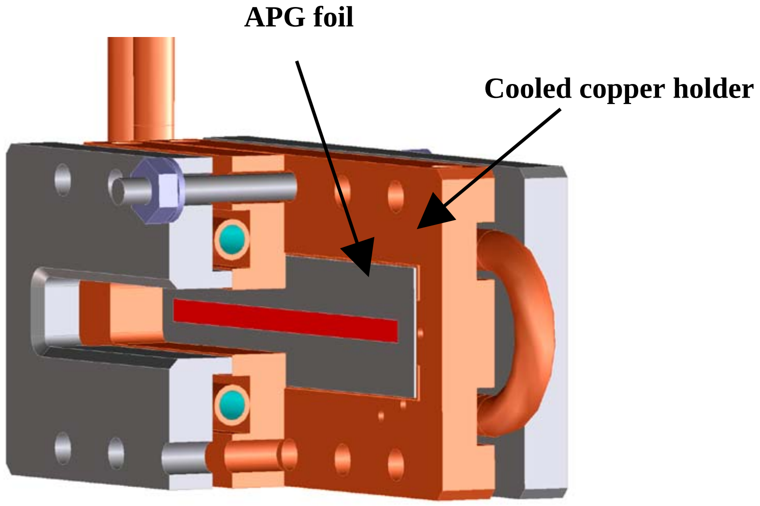

Fig. 5: Design detail

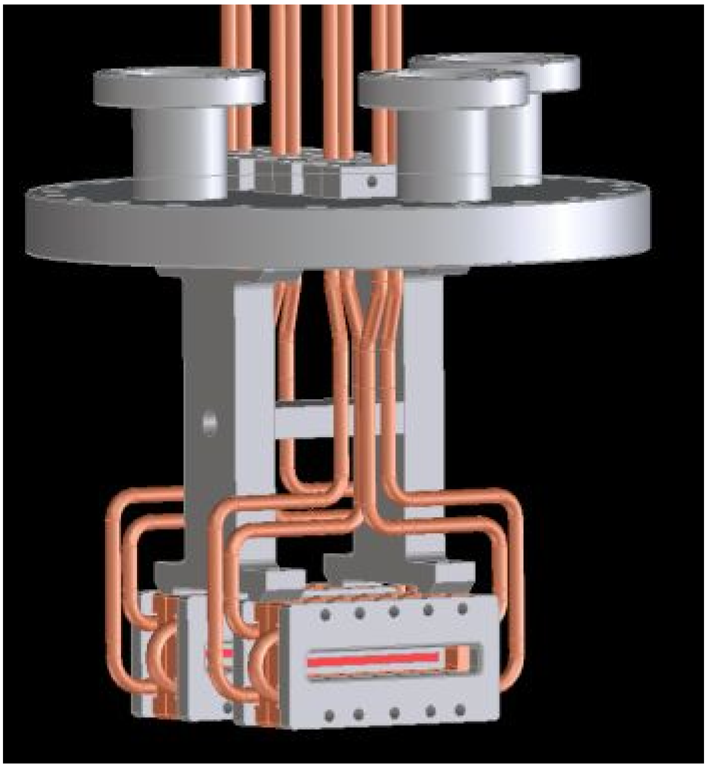

Fig.6: Final assembly using two carbon foils

2.2 Tests

To detail the final assembly, tests were performed in order to find more information on how to practically handle the graphite foil, to find the best compromise between clamping pressure and heat conduction limiting the stress of the foil at the contact area.
Two different foils were considered: the APG foil from K Technology Corporation and the HOPG ZYB foil from GE Advanced Ceramic since they both have similar thermal properties. Most of the tests were done on the APG foil because of its lower cost and better availability. The first noticeable difference between the two foils is the appearance. The APG foil is a

rough graphite foil, it presents visible peaks and valleys on the surface. The HOPG foil is a shiny flat foil that has been gone through a very complex cleaving process. After having compared samples of the two foils under a TEM microscope we can see that the APG foil, despite still presenting a layered structure, is more amorphous than the HOPG foil.

Both foils can handle very high pressure (up to 10000 psi) if this pressure is balanced but they are very weak in bending. So it is very important before clamping the foil between the two copper frames, to anneal the copper and flatten surfaces that will contact the graphite.

We tested 0.125, 0.25 and 0.4mm thick APG foils and 0.25 and 0.4mm thick HOPG foils. HOPG foils minimum thickness is ~ 0.25mm. Reducing the thickness is very difficult and compromises the strength of the foil. The 0.125mm thick APG foils instead were also available.

In all cases we were able to clamp on annealed copper up to the copper yield point, with no visible damage to the foils.

We decided to clamp the assembly at the pressure that would start copper yield because this pressure would have resulted in enough contact area between foil and copper to transfer the heat limiting the stress at the contact area.

To simulate a worst case stress created by the CTE mismatch between the frame and the foil, the clamped assembly was cycled in a vacuum furnace.

Four 0.4mm thick APG foils have been cycled in the furnace. Each cycle consisted in heating up the foil, clamped into the assembly, to 300ºC for 20 minutes and cool back to room temperature. After one full cycle 3 foils out of 4 presented a vertical crack [Fig.7, 8].

After having cycled the same assembly for 6 times (RT-300C-RT) we didn't notice any difference in the foils. The foils that after one cycle were presenting the vertical crack, were still presenting the same vertical crack but no other cracks had appeared. The foil that didn't crack stayed intact after the full 6 cycles.

Given the rough nature of the APG material, it is possible that the cracks formed in correspondence of a pre-existing discontinuity. Being the APG material with a rough surface it is possible for cracks to appear at the interface.

The tests were very conservative because the actual frame temperature should never exceed a peak of 240ºC on a small area plus, despite the cracking, the material was still maintaining its strength, and the repeated cycling effect didn't seem to change its characteristics after the first cycle, so the behavior was predictable.

We also tried to polish the APG foil in house to reduce the possibility of cracks formation, but we later found out that the process we were using was decreasing the strength of the material and we didn't proceed any longer in the effort.

The same thermal cycle has been applied to one 0.4mm thick HOPG foil and no cracks were observed.

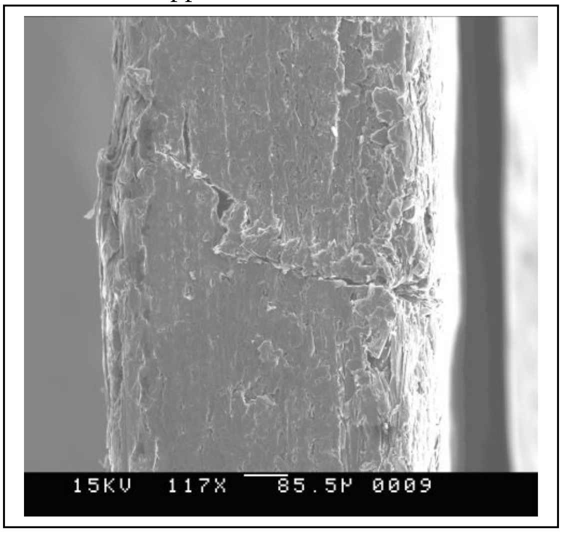

Fig 7: Picture of the APG foil crack through its thickness, taken with a SEM microscope.

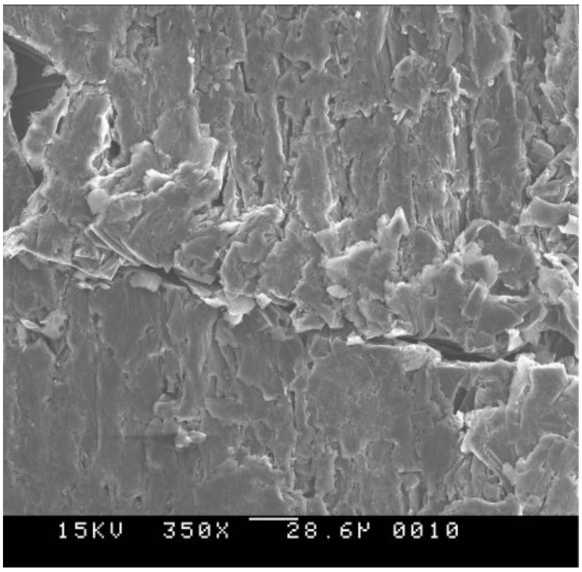

Fig.8: Detail of crack shown in Fig.7

The last unknown was the thermal conductance at the contact area between graphite and copper. Was a rigid clamp without any kind of interface sufficient for what we needed, or did we need to add an interface material to increase the contact area and improve heat transfer? From the previous tests conducted on clamping the foils to the copper frames we saw that the copper was completely deforming onto the graphite foil, also finite element analysis were showing that a smaller percentage of the contact area would have been enough to conduct the heat out in an appropriate way. Therefore, we decided to test the clamped assembly without adding any interface material in the contact area.
We tested the two different foils clamped as designed, using an electron beam source [6], we were able to simulate the power density in conditions very similar to those found during use. It should be pointed out that the use of an electron beam source is a conservative test since all the power is deposited in the front surface of the foil.

The assembly with 0.125mm thick APG foil was tested without damage to 61 W/mm^2 (equivalent to 490 W/mm^3 volumetric load in the 0.125 mm foils).
Note that in the worse case of W11 wiggler if the total power was deposited on the front surface, this would correspond to a power density of 17.5 W/mm^2 that is still 3 times less power than our worst-case test.
The assembly with 0.2mm HOPG foil was also tested to 61W/mm^2 but after a load of 2000W for 10 minutes, the foil suffered two horizontal cracks, through the thickness: no light could be seen through but the pattern existed on both sides of the graphite.

3. Conclusions

Prior to the W11 wiggler upgrade the entire assembly with two 0.125mm thick APG foils was installed in the beam line and operated for 4 months with no visible damage in the foils[Fig.9,10,11]

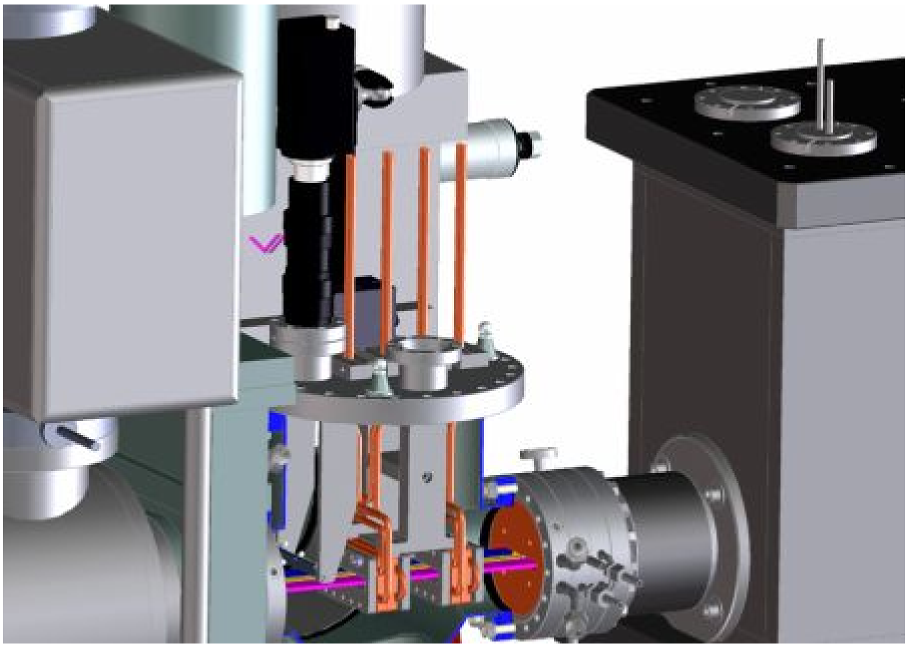

Fig.9: Models of Filter assembly in location in beamline 5.0

Fig.10: Final assembly installed in January in bl.5.0 consisting of two .125mm thick APG foils

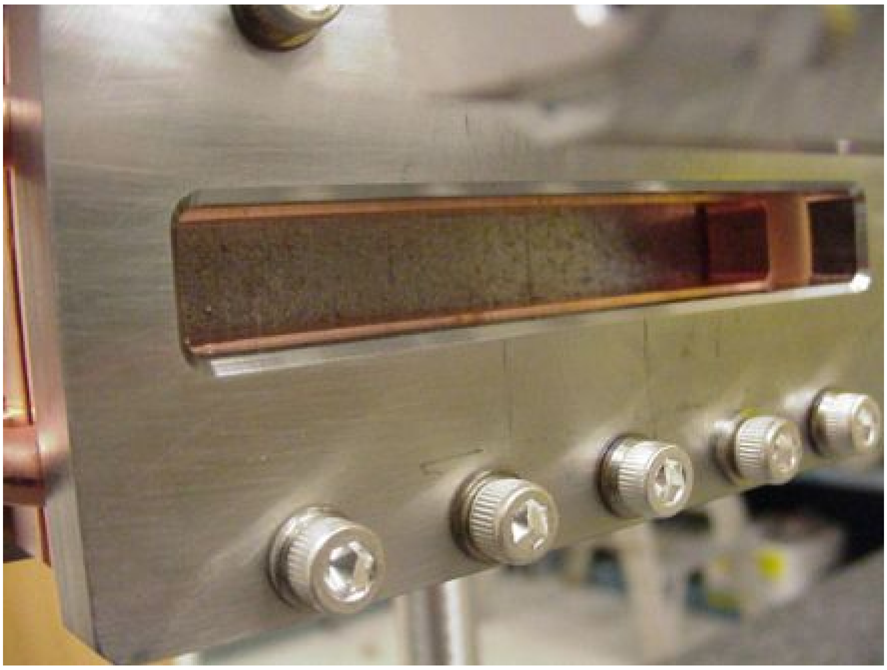

Fig.11: Filter assembly after 4 months operation with 2600W power load (No observed damage)

The final design with two Annealed Pyrolitic Graphite foils 0.2mm thick has been installed and it is now operating with the new wiggler.
Thermocouples have been added to the two copper frames and an optical camera has been installed to provide diagnostic during operation.

4. Acknowledgements:

We would like to acknowledge all the people that helped in the realization of this project and contributed to its successful outcome:
Mark Montesano- K Technology Corp.
Arthur Moore- GE Advanced Ceramic
Bob Watson and Richard Nygren- Sandia National Labs
Edward Savage-ESCO
Jim Savino -CHESS
Carol Corradi and Simon Morton-LBNL.

5. References:

[1] "Design of a Graphite-Filter/Beryllium-Window for CHESS Wiggler Beam Lines"- Qun Shen, Karl Smolenski, Ernest Fontes- SPIE Vol.3151.
[2] "High Heat Load Graphite Filter Design at CHESS Wiggler Beam Lines"- J. J. Savino, Q. Shen, A. Pauling , E. Fontes, G. Strieter- SRI 2003 Proceedings.
[3] K-TECNOLOGY CORP. Contact: Mark Montesano, http://k-technology.com.
[4] GE Advanced Ceramics, http: http://www.advceramics.com.
[5] "Calculation of incident, transmitted and absorbed power for the BL.5.0 Carbon Filter" Steve Marks-LBNL Engineering Note #AL 4081
[6] ESCO Integrated Manufacturing, Concord, CA. Contact: Edward Savage