Development of Air-cooled Disc Amplifiers for Vulcan

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Introduction

In this section we report on the work undertaken at the STFC towards the development of an air cooled flash-lamp pumped disk amplifier to increase the repetition rate of high energy flash-lamp pumped lasers. The overall aim is to improve the current repetition rate from one shot every 20mins to one shot every 5 minutes.

Initial testing of an amplifier at 5 min repetition rate

To determine the extent of the heating problem an existing Vulcan amplifier was operated at a 5 minute repetition rate in an off-line facility. Under normal conditions there is no active cooling of any parts of the amplifier. However, after a laser shot air is blown over the flash-lamps to cool them for typically 20mins. To quantify the extent of heating a number of thermocouples were mounted in the amplifier. One of the thermocouples was installed into one of the disks of the amplifier by drilling a hole into the glass and then mounting the thermocouple into the hole using heat conducting paste. The amplifier was operated at standard voltages (20KV) and currents (19KA) to best mimic typical operating conditions. However, there was no energy extraction through gain.
Figure 1 shows the temperature recorded by the thermocouple at the centre of one of the disks in the amplifier. As can be seen there are a number of fast temperature spikes that we attribute to the thermocouple being directly heated by the flashlamps by absorption. It can also be seen that a steady state temperature of nearly 60^{O}C is reached from an initial temperature of 20 ^{O}C after about 40 shots. This temperature rise was reduced when there was a constant flow of air across the flash-lamps to cool them. This would be expected since in addition to the normal quantum defect heating the flash-lamps themselves get very hot and then transfer this heat into the body of the amplifier.

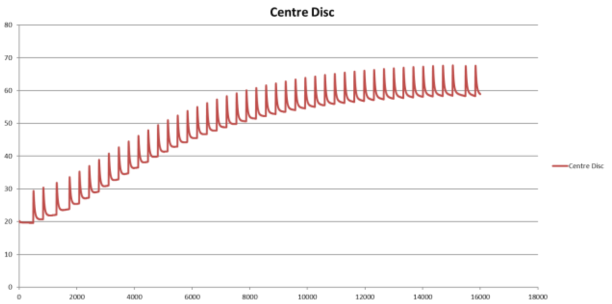


Figure 1. Temperature rise of the thermocouple mounted in the centre of the disk.

Modelling of the heating due to the flash-lamps.

To model the heating due to the flash-lamps two methodologies have been employed for 2 different temporal regimes. For the prompt aberrations a numerical model has been developed to model the spectral output of the flash-lamps and this has been combined with a Zemax [1] illumination model to understand the intensity of the pump light in the amplifier. The combination of these has been used to resolve the temporal rise within the amplifier in the <1ms regime where thermal conduction within the amplifier can be neglected. This predicts only modest rises in the temperature of the amplifier media. However, due to the non-uniform illumination a non-uniform temperature profile is generated in the gain medium which leads to the appearance of prompt aberrations that degrade the beam quality of the laser beam passing through it. Figure 2 shows an example of the predicted temperature rise and wavefront for a disk in such an amplifier. The cooling is calculated by solving the heat equation and assuming constant cooling at the surfaces. For the longer term we have used the temperature rises observed in the offline testing to estimate a heating rate due to the temperature increase of the flash-lamps to develop a model that can be used to model different cooling geometries. The solutions to this model is achieved using commercial FEA software [2], an example of the software and the mesh generated to solve a prototype cooling scheme is shown in figure 3.

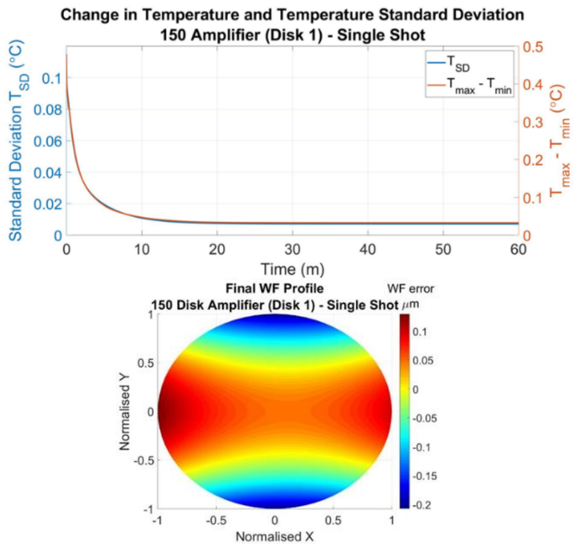


Figure 2. Example temperature rise (top) and wavefront degradation (bottom) predicted by caluculated from the quantum defect only.

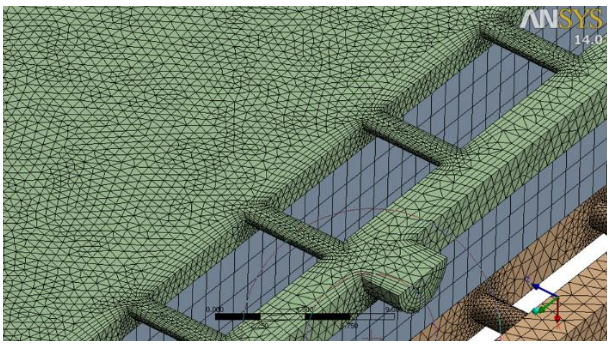


Figure 3. Example of the mesh created to study a prototype cooling scheme.

Modelling of air-cooled design.

Using the heating models outlined above a number of cooling geometries have been studied using air as the cooling medium. It is clear that as a relatively poor thermal conductor the difficulty in extracting the heat from the amplifier glass is severest for the central sections of the disk. The solution that we have pursued is to divide the disk into two halves and look to cool the now 4 faces rather than 2. We have looked at 2 different cooling scenarios, a low air mass high pressure design and a large air flow low pressure design. It was predicted that for the former the nozzles required to create the cooling jets could lead to spatial variations on the cooling of the amplifier medium. Figure 4 shows the predicted gas velocities for an example air flow through the nozzles. To confirm the cooling effect an experimental test-set-up was created that comprised a pair of glass slabs to be cooled and heated from either side by conventional bar heaters (Figure 5). In this way the amount of heating and cooling could be controlled more systematically than when using an amplifier. Figure 6 shows the temperature changes for the centre of the disk when it is heated for a minute by the heaters and then with the heater off for 4 minutes. In the blue trace there is no cooling applied, in the red trace there is cooling applied at a rate of 40l/min of air and the green trace shows cooling at a rate of 70l/min of air. In both these instances the air is derived from a compressed air bottle. It was found that for some tests the temperature of the air changed as the flow rate was increased. As can be seen there is some cooling, although there is not a significant difference in the steady state temperature reached when the flow rate is increased from 40 to 70 l/min.

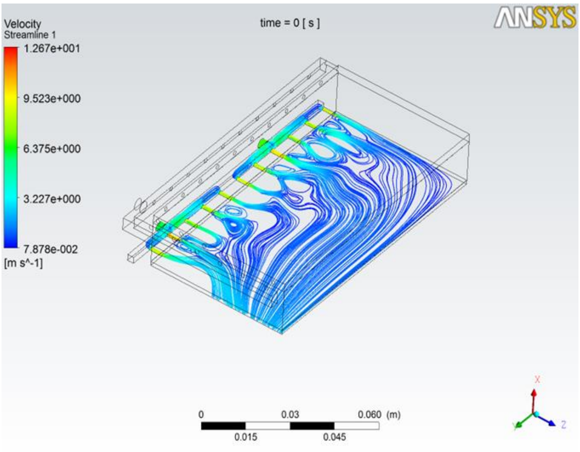


Figure 4. Showing the predicted gas velocities for an example nozzle design.

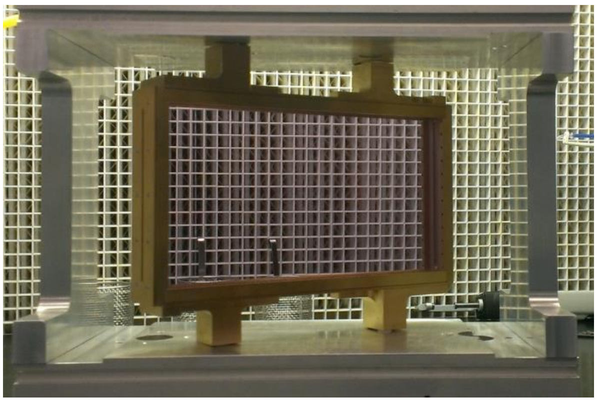


Figure 5. Set-up to investigate cooling using bar heaters.

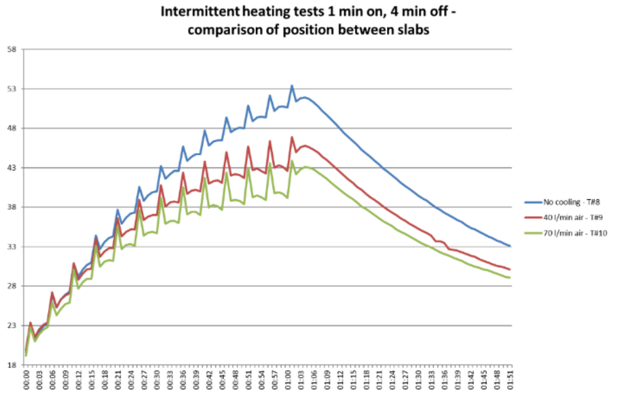


Figure 6. Influence of different flow rates through the nozzles on cooling.

For the second design where there is a larger air mass crossing the amplifier disk figure 7, there are no nozzles so there is a more uniform cooling and subsequent temperature profile. There are 2 air ducts to supply cool air to one side of the disks and another to extract the air (the yellow arrow indicates expected air-flow path). The flash-lamps have a separate cooling circuit. This is shown in figure 8 which shows the top surface temperature profile for the lower slab for each pair of slabs in the amplifier. The temperature variation across the slabs is predicted to be 1.6 ^{O}C at 5 min operation.

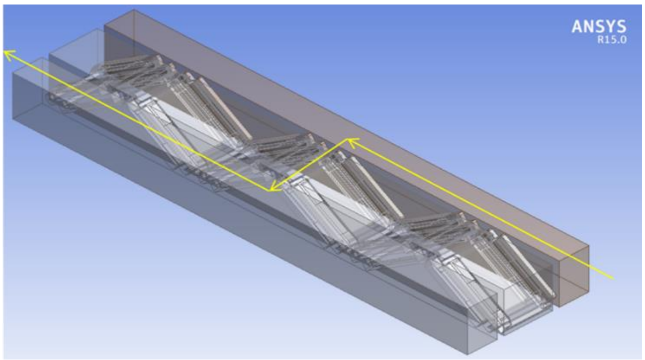


Figure 7. Model for the large mass flow amplifier.

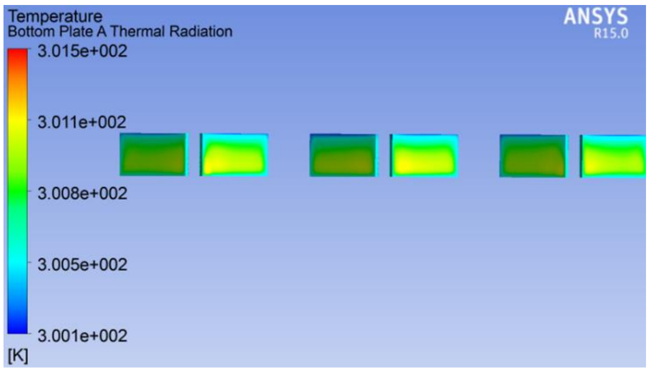


Figure 8. Predicted temperature profile for top surface of the lower half of each pair of slabs in the modelled amplifier.

Prototype Development

Based on the modeling undertaken we have designed and constructed a prototype amplifier. An artist's impression of the inside of the amplifier is shown in figure 9. The pairs of disks are held in a cassette to aid with their installation and extraction. Air is then directed past the front and rear faces of both of the disks. Special reflectors are required so that they fit between the disk cassettes and allow the air to pass from the manifold and into the amplifier body.

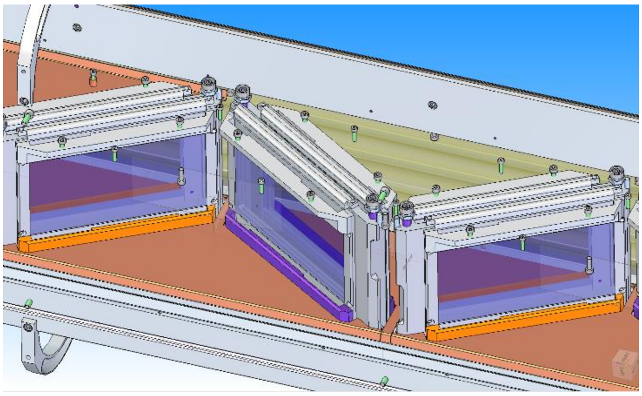


Figure 9. Artist's impression of the prototype amplifier.

A picture of the assembled amplifier installed for testing is shown in figure 10. The amplifier has had a number of thermocouples installed at varying positions within the amplifier to monitor the temperature changes during operation. Preliminary results are shown in figure 11, where a single shot has been taken and no cooling applied (left) and with full cooling (right). As can be seen the cooling makes a significant impact on the cooling rate of the channels shown in the plot. Further tests are required to confirm the efficacy of this cooling scheme and to see whether cooling can be applied continuously or if it will need to applied between shots and then stopped for a period before/ during shots to prevent air turbulence from degrading the laser beam.

Figure 10. Photograph of the prototype amplifier in place for testing in the Vulcan amplifier.

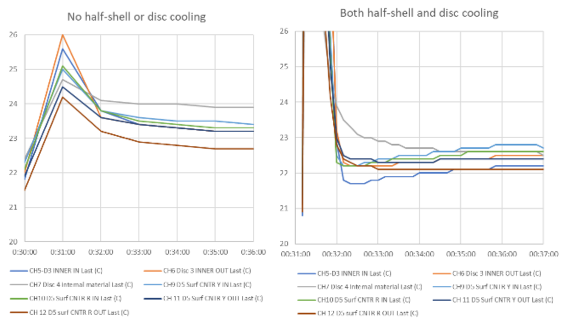


Figure 11. Preliminary test results for a single shot with no cooling (left) and with cooling (right).

Development of prompt aberration measurement.

Whilst it is important to measure the temporal temperature evolution within the amplifier, an arguably more important parameter are the aberrations that are generated in the glass disks. To measure and confirm the validity of the model developed for the prompt aberrations and to monitor the temporal evolution of the wavefront we have developed a device to enable the temporal evolution of the prompt aberrations experienced by a laser beam passing through an amplifier to be measured. The concept of the device is based on splitting the original beam into four sub-apertures and focusing each of these beamlets onto a position sensitive device (PSD) as shown in figure 11 (top). A reference wavefront is taken by passing an un-aberrated beam through the test device, deviations from a plane wavefront cause the spots to move on the PSDs (figure 11 (bottom)). Since a PSD has a response rate of the order of ~10KHz it can be used to measure the evolution of the wavefront on time scales as short as ~100µs. This negates the need for multiple shots to measure the evolution of the wavefront and allows an easy readout using a data logger for longer durations. The output from the PSDs can be used to reconstruct the wavefront degradation by the use of Zernike polynomials. With 4 PSDs the tip, tilt, astigmatism and defocus can be estimated. Further channels could be added to increase the number of polynomials that could be retrieved. For further details, see reference 3.

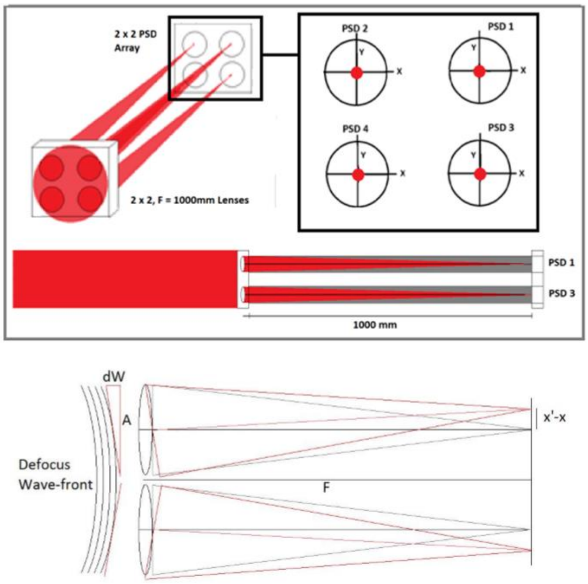
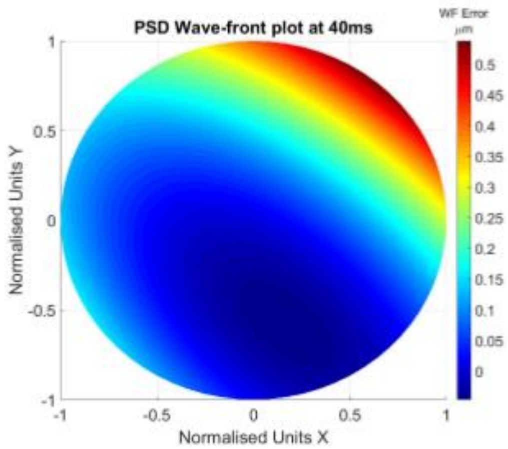


Figure 11. Schematic of the PSD wavefront measurement device.

This new device has been bench-marked using an existing Vulcan amplifier. Figure 12 compares the wavefront measure using this technique (top) and that produced by a traditional commercial Shack-Hartmann wavertont sensor (bottom) showing good agreement. This device will be used the measure the wavefront generated by the prototype.



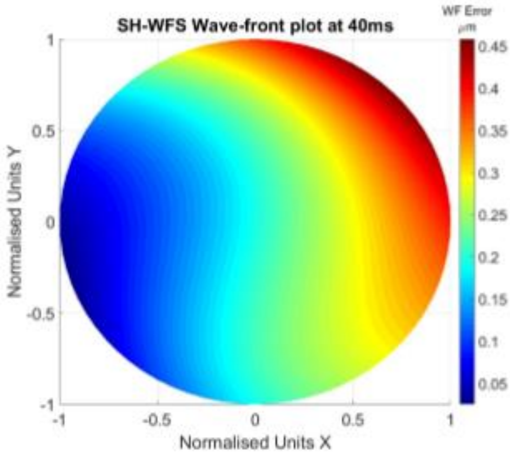


Figure 12. Wavefronts of the laser beam as measured by the PSD scheme (top) and a commercial Shack-Harmann sensor (bottom)

Conclusions

In this article we have presented the work that we have been undertaking into the development of air cooled amplifiers. We have shown the initial promising results derived from early testing of a prototype amplifier.

References

1. https://www.zemax.com/products/opticstudio
2. https://www.ansys.com/en-gb
3. M. Ahmad, M. Galletti, P. Oliveira, E. Dilworth, D.J. Robinson, M. Galimberti, A.J. Crawford, I. Musgrave and M.J.D. Esser, 'Time-resolved thermally induced aberrations in a flash-lamp pumped Nd:Glass disk amplifier using a 2 x2 position sensitive detector array', Rev. Sci. Inst. **90**, 123106 (2019)