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Automatic Beam Guidance and Mode Control System (Distributed Optical Energy)

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Abstract

A beam control system has been developed which maintains automatically size, alignment and mode of a CO_2-laser beam over a long beam path in closed loop. Trials of the integrated system shows that at a distance of 40m pointing accuracy of better than 0. 5mm can easily be achieved (i. e. 12.5 µrad), the beam size being stabilised to less than 2°/0 variation. The laser mode is optimised to the best available M^2. All control functions are designed to work in conjunction and together with modern and economical CNC-PC.

1 Introduction

The growing number of large laser facilities, e.g. the Laser Welding Institute (UK) or the Institut für Strahlwerkzeuge (Germany), and the interest of car, ship or nuclear industry in remote laser applications has highlighted the problem of the distribution and guidance over long laser beam paths. In these facilities the output power of a single high power carbon dioxide laser is used at multiple workstations, which may be separated from the laser source by tens or even hundreds of meters, The problem of laser beam stabilisation over such distances is especially severe, if the workstation is movable as it is in a gantry. Small disturbances of the beam guidance systems, the laser mode or misalignments of a movable workstation result in large variations of the beam position and beam size at the workstation which in turn will result in poor quality cutting or welding performance.

In order to overcome this problem an automatic beam alignment system has been developed within the scope of the BRITE EURAM Project BE 4046. This system automatically adjusts the size and alignment of the laser beam at the workstation and comprises three different parts: a beam mode control device (developed by Lessmüller Lasertechnik GmbH, Wegmann Baasel Laser GmbH and Applikationslabor für Lasertechnik GmbH in Munich), a beam size control device (developed by Lessmüller Lasertechnik and Empressa National de Optics SA) and a beam alignment control device (developed by Liverpool University and British Nuclear Fuels plc). All of these devices have been equipped with feedback detectors in order to ensure operation under closed loop control. The design of the system allows operation and control within any laser beam at power levels up to more than 10kW.

2 Technical Description

2.1 Set-up of the Integrated System at CETEMA

Fig. ***1*** shows the set-up of the long beam path system at CETEMA/Madrid, where the individual beam control devices developed by the collaborators were integrated and finally tested in one single system. It is comprised of the following control systems (main components in brackets):

- ‘Beam **Mode** Control Device (mode sensor, motorised output mirror)
- Beam Size Control Device (telescope and size sensor)
- Beam **Alignment** Control Device (2 alignment sensors and 2 motorised mirrors).

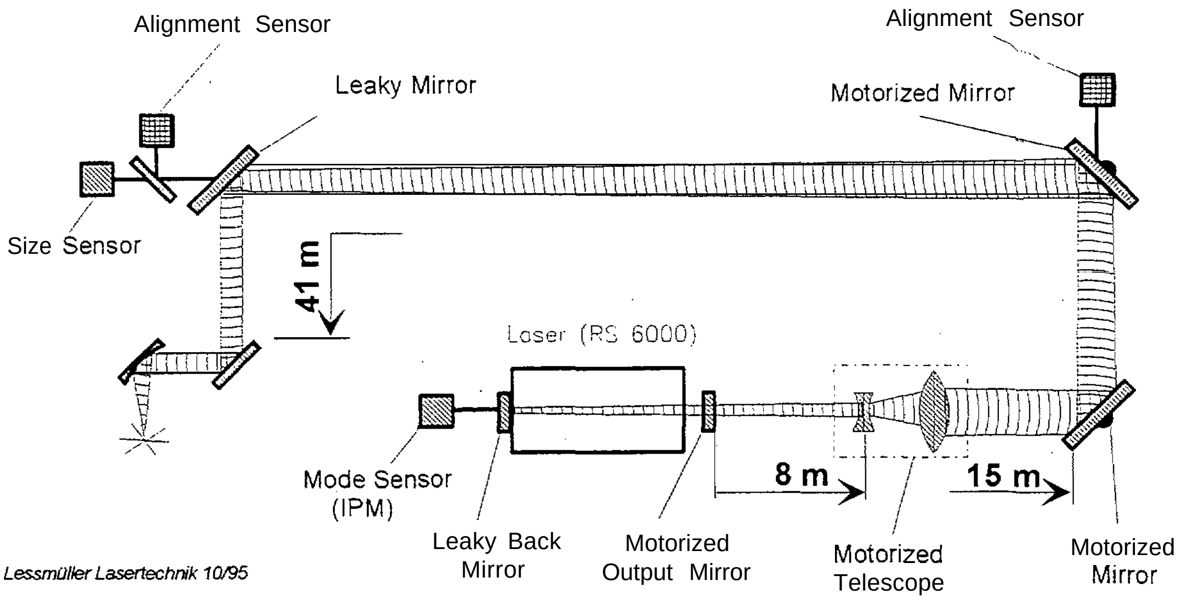

Fig. I Beam guidance system at CETEMA.

A ROFIN SINAR RS6000 fast flow laser with a maximum output power of 6kW is used in the system. This laser may run with a TEM20 (M^2= 5.8) mode for high power processing or using an intracavity aperture with a pseudo TEMOO mode mixture (M^2= 2.5) at 2000W. The system can be seen to have an overall path length of41 m. The distance between the telescope and the laser is 8m in order to have enough room for the installation of a beam switch and other equipment (not shown in ***Fig. 1***) which was needed to use the laser for different applications at the test site,

2.2 Beam Mode Control Device (BMCD)

Fig. 2 shows the design of the Beam Mode Stabilisation Device. It comprises of a three-axis motorised output mirror, a partially transparent back mirror, two folding mirrors and a specially developed intensity peak sensor. Inside the sensor two detectors measure the intensity at the centre and periphery of the laser beam. The mode sensor is separated from the back mirror by a distance of 5m in order to obtain a measurement which is more comparable with the far field intensity of the laser beam. The control program uses self-learning algorithms to adjust and stabilise the resonator by maximizing the peak intensity and laser power. Thereby the intensity distribution and the beam quality is optimised (the M^2 factor is minimised).

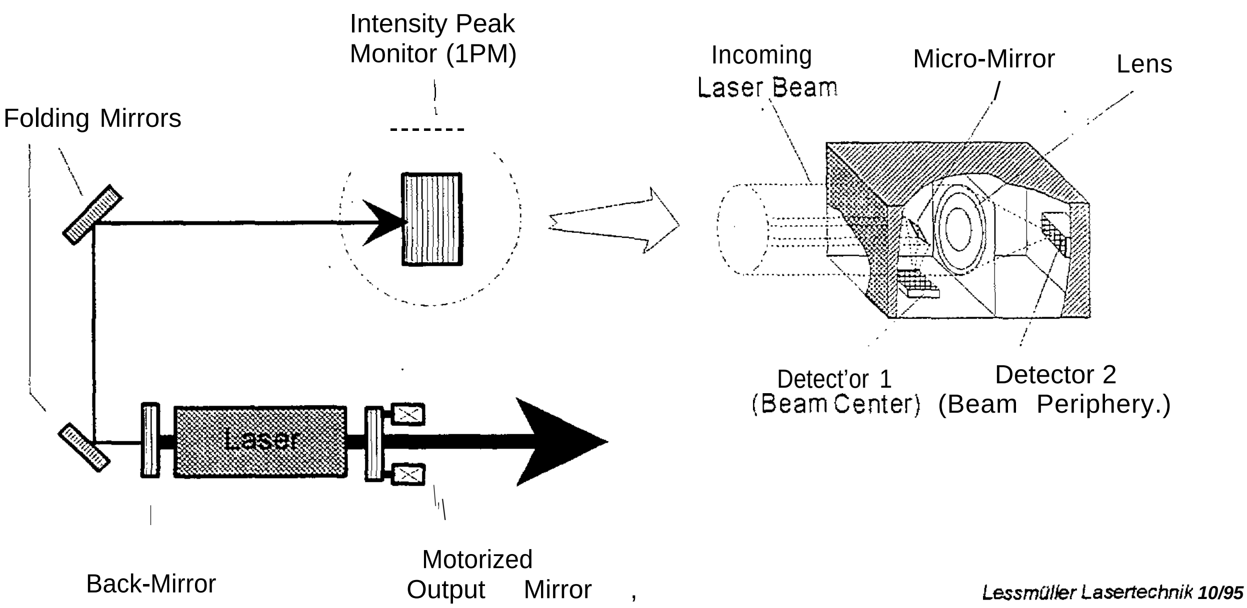

Fig. 2 Design of the beam mode control device.

The program is flexible *to allow* control of different types of lasers and mode structures like the TEMOO and TEM20 modes of the 6kW project laser.

2.3 Beam Alignment Control Device (BACD)

Long beam path alignment, i.e. the pointing vector, is affected by the laser itself and by the optical elements along the path. Wandering of the laser pointing is mainly due to changes of the resonator geometry and intracavity properties by heating of the laser. In the case of gas lasers with gas flow transverse to the resonator axis the variation of the refractive index inside the heated gas flow also has to be taken into account. Both effects lead to variations of the alignment, which are called 'beam steering'. In a similar way distortions of the geometry of the mirrors and their mounts outside the resonator will change the alignment too.

In order to guarantee that the laser beam will always enter the aperture of the working head at its centre without clipping and that the angle of incidence is vertical - which is even more crucial for the position of the focus - these misalignments have to be corrected.

Within the scope of this project an automatic alignment system has been developed which operates in closed loop control. It consists primarily of two steerable mirrors, each part of a two-axis goniometer and two alignment sensors, whose positions in the beam path are shown in ***Fig. 1***. The alignment group, Liverpool University (W M Steen, M. Sparkes) and BNFL (W Perne) undertook an extensive survey to choose the best signal sampling technique. This included more direct measuring methods like edge feeler and spinning needle concepts, as well as indirect methods like phase-locked triangulation of acoustic shock waves in mirrors, The solution was finally the development of a leaky silicon mirror. The use of silicon as mirror substrate enables the design of large but cheap mirrors, whale the fraction of the energy which penetrates the silicon is still high enough to be measured by detectors.

The set-up of the beam alignment sensor is shown in ***Fig. 3***: The incoming beam is re-fleeted at 90° by the 125mm diameter silicon leaky mirror and a small fraction (1,1 *10-s for circular polarisation) passes through the silicon. This beam fraction is then focused by a lens and hits the surface of a beam splitter which directs it to fast response thermopile detectors.

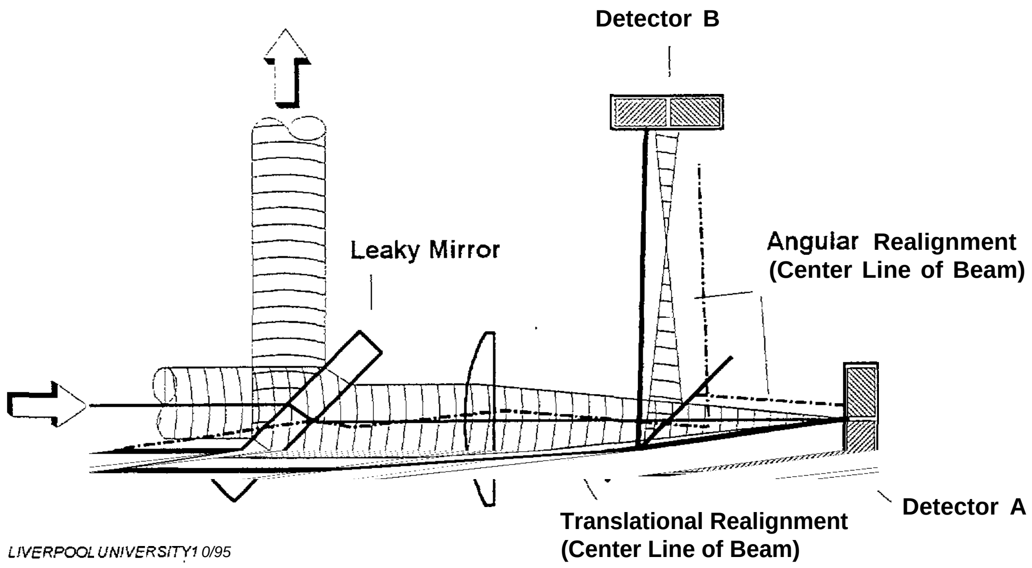

Fig. 3 Design of beam alignment control device

Each detector is of a quadrant type for measuring the beam position. A two detector Hartmann array design is necessary to separate angular and lateral displacements. Detector A is at the focal point and measures angular deviation between optical axis and real incoming beam. Detector B is off the focal spot to measure the sum of angular and lateral shift (***Fig.*** 3).

If the distance between the steerable mirror and the attached sensor is big enough that the beam stays always paraxial then the position information obtained from the sensor is primarily a result of lateral displacement. In such case of a 'long beam path' the alignment sensor may be simplified by removing the angular detector, (Detector A, see ***Fig. 3***).

2.4 Beam Size Control Device (BSCD)

System Design

The diameter of the laser beam increases significantly if the beam emerges from the laser resonator with a small diameter and is propagating over a long distance. After a path 40 m the beam diameter of the RS6000 in TEM20 mode increases by a factor of three to about 100 mm, which requires large, heavy and expensive optical components. The focused spot diameter is inversely proportional to the beam diameter, thus the spot size is different all along the path.

In order to avoid these problems telescopes are used for long beam paths. In the case of high power lasers these telescopes are made of reflective optics, i.e. mirrors, and have a fixed focal length. For example, in gantries the focal length is set for minimal divergence and symmetric variation along the traveling path. In such installations the beam diameter still varies from 10 to 20% along a distance of 20 m (see the informative BIAS report, Heidenreich [1]) so the focused spot diameter varies by the same factor. This size change has an enormous impact on cutting and welding processes as processing depends on the intensity or power density which is proportional to the square of the spot diameter.

The BE4046 project chooses a more ambitious solution for maintaining constant beam diameter at the focusing head by developing a motorised telescope. This telescope operates in a closed loop and gets its feedback signal by a size sensor, which measures the actual beam diameter at a position near the workstation. The advantages of this solution are:

- control of the beam size at any position along the path
- the beam size at the workstation can be chosen within a particular range
- constant beam diameter at the working head independent of the laser power

Closed loop control opens the window for the use of telescopes with refractive optics (i.e. lenses) for high power applications. Until now power levels over 2 kW have been difficult to use due to heating of the lenses. This 'thermal lensing' results in an unpredictable runaway of the telescope focal length. The same is true for the output coupler of the laser with power changes and surface degrading in time, By using the beam size control device in closed loop these changes of focal length can be corrected for and thus maintain a given beam size at any point.

Telescope

The telescope of the B SCD is water-cooled and consists of two ZnSe lenses with standard antireflection coatings. The input lens has an aperture of38 mm and is additionally cooled at the external optics} surface by a circular air flow, The output lens has a diameter of 85 mm. The high accuracy focus mechanism is protected by several mechanical means against tilting, the focal length is adjusted, backlash free, by a stepper motor which is driven directly from the control PC by a M20 micro stepper card from Lessmüller Lasertechnik, München.

Size Sensor

The size measuring sensor in the long beam path is positioned behind the last bending mirror near the working head (see *Fig. 1*). It is combined with the alignment sensor making use of the same leaky mirror and focusing lens. This was possible because the alignment system needs only one detector at this location.

The set-up of the size sensor is based on a measurement method developed by Lessmüller Lasertechnik. Due to its design the size sensor is called 'WINKER' (see *Fig. 4*). The fraction of the incoming beam which passes the leaky silicon mirror is focused by a large lens and passes then a beam splitter where a fraction is divided towards the alignment detector (not shown in the figure below). The other part reaches the winker and finally the detector.

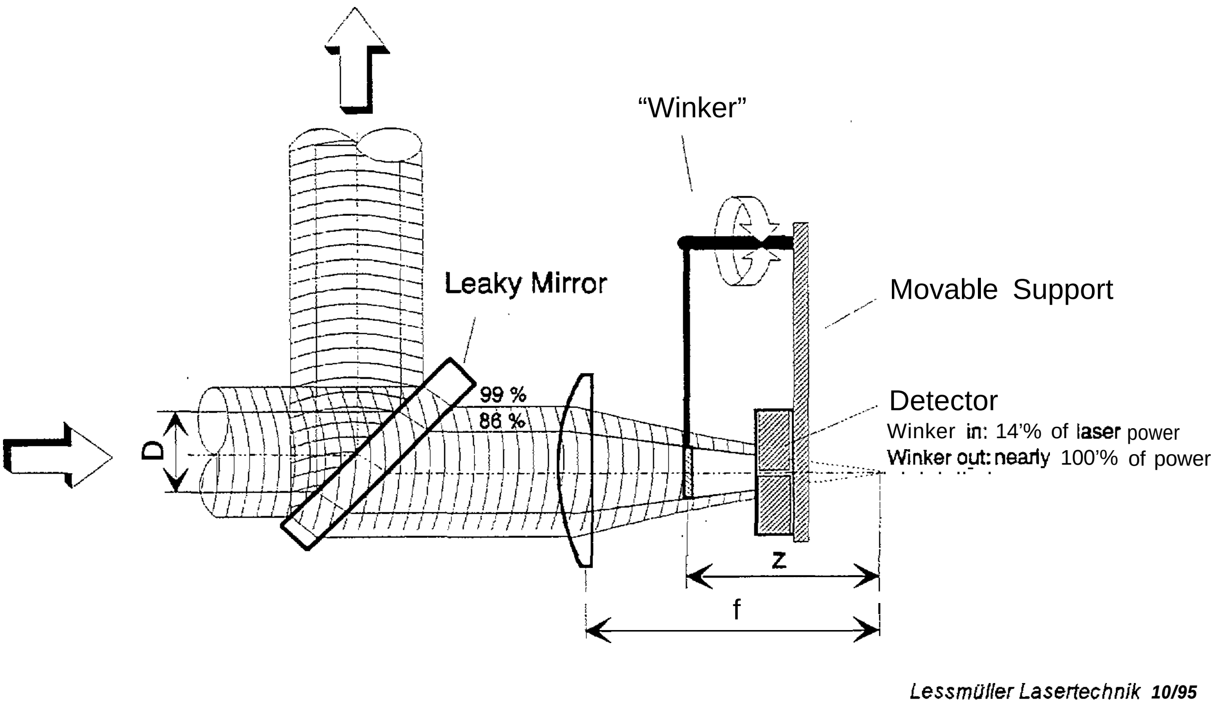

Fig. 4 *Set-up of beam size sensor*

The detector is a fast thermopile quadrant type of the same type used in the BACD. The winker is a small reflecting plate with diameter *din* front of the detector that steadily swings in and out. Detector and winker are mounted together on an arm which is able to move along the sensor z-axis and to swivel and tilt in addition orthogonally.

During start-up the winker is moved to a position z = $f\ d/D$ where ***f is*** the focal length of the lens, and *D is* the desired beam diameter, The beam size is then adjusted by the motor-ised telescope until the ratio of the power on the detector with winker in and out is equal to (1-0.86). In this case the plate has reflected 86% of the laser beam, i.e. its diameter *d is* equal to the diameter which contains 86°A of the laser power and is commonly used as definition of the beam diameter. This method of measuring beam sizes is accurate for any kind of mode as it is based on the effective radius $D=M * \omega (z)$. For a pure TEMOO mode withA42 = *l* the ratio is *0.86*, while for a pure TEM20 mode with $M^2 = 5$ the ratio at the effective radius should be 0.92 [4].

The winker nose is able to tilt and swivel and follows all beam movements by centring the detector to the beam. This allows an easy preliminary alignment of the sensor by accepting poor linearity between the winker z-axis and the optical axis of the incoming beam and also permits successful operation of the size sensor even with alignment control switched off. The sensor is motorised with little stepper motors, all movements are filly controlled by computer.

2.5 **Integrated System Control (HOST)**

The system is controlled by a program running, on a standard 486 personal computer. The program itself contains three individually developed parts referring to size, mode and alignment control devices of the integrated system. An additional part enables parallel operation of each device. The latter part is called HOST and is embedded in a multitasking environment 'RT-Kernel' developed by *On Time*. The processor is switched between the particular program parts (tasks) several thousands times per second. This gives the advantage that each task can be programmed as if it had it's own computer.

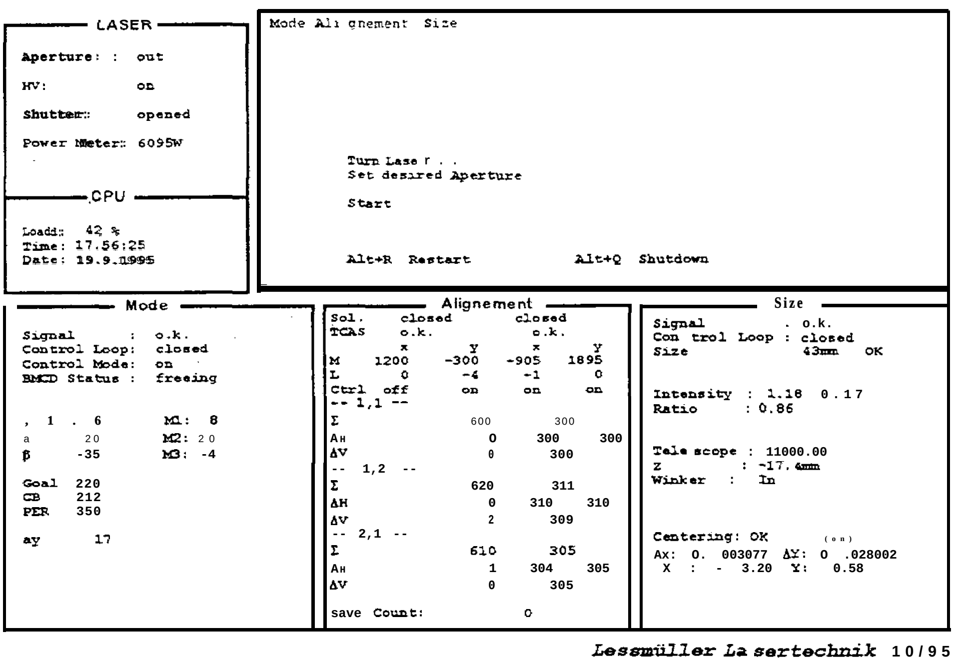

Fig. 5 Display of the HOST program

The display of the HOST program is shown in ***Fig.*** '5. The main parameters of each control device are shown in separate windows at the bottom of the display while the status of the laser itself is displayed in the left-hand upper corner of the display. The larger right-hand upper part of the display refers to a dialog window to operate the integrated system as a whole. This allows start and shut down routines following a flowchart structure. Special dialogs with the sub systems for maintenance purposes are also handled in that dialog window.

3 Results

3.1 Beam Mode Control Device (BMCD)

The laser is stabilised on-line in transversal mode. Several trials were made to prove the performance of the mode control. In one of these trials the laser was first manually adjusted. This resulted in an increase of the power in the central peak of 25°/0 while the. total power remained constant, The BMCD was then turned on and an increase of the peak power to 149°/0 in comparison to the original power was observed. It is very interesting to note that at the same time the total power could be increased slightly.

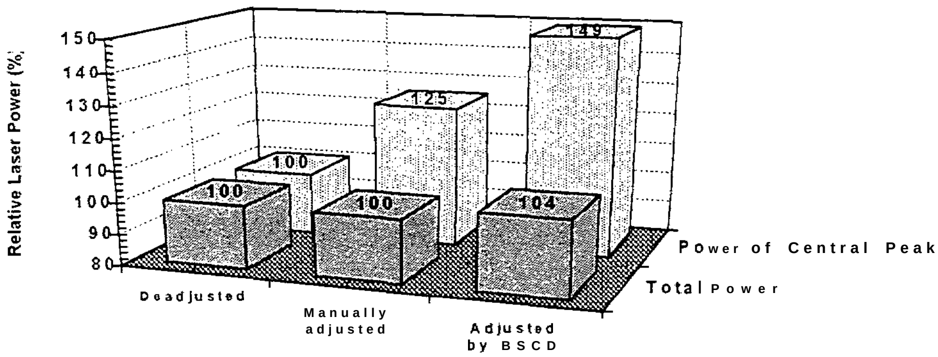

Fig 6 Effect of BMCD on the total laser power and on the laser power in the central peak.

In another experiment the output mirror was first manually adjusted to produce an optimum mode pattern (shown at the left side of *Fig 7*) at a distance of 6.9m from the output mirror. Afterwards the resonator was manually misaligned until a poor mode was observed (centre).

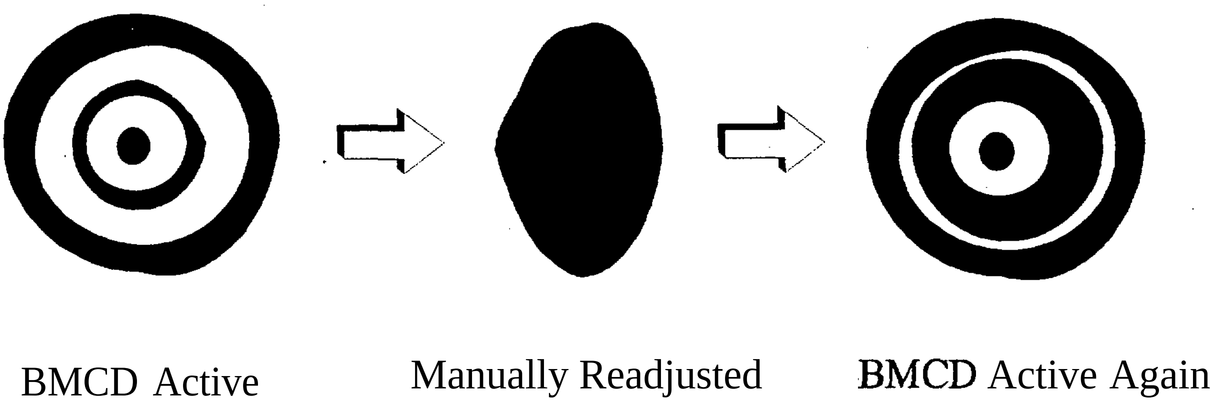

Fig. 7 Correction of manually de-adjusted output mirror by Mode Control Device.

The mode control was then turned on and after 20 seconds to 40 seconds the control program signalled that the automatic beam mode adjustment has been completed and recovered the

mode. The intensity pattern in the paper burn shows that the laser was running in a nearly perfect astigmatism free TEM_{20}-Mode again (right side of
Fig. 7).

3.2 **Beam Alignment Control Device (BACD)**

In order to prove that steering of the beam can be corrected by the beam alignment control device the deviation of the beam was monitored using a PROMETEC at the workstation.

Fig. 8 shows that without the BACD the deviation evenly increased and reached a value of 4mm after 15 minutes. When the BACD was turned on these deviations are limited to less than ±0.5mm. Uncontrolled beam movements, i.e. with the BACD off, during testing at 40m damaged a cutting nozzle and a Prometec, which confirms the need for alignment control.

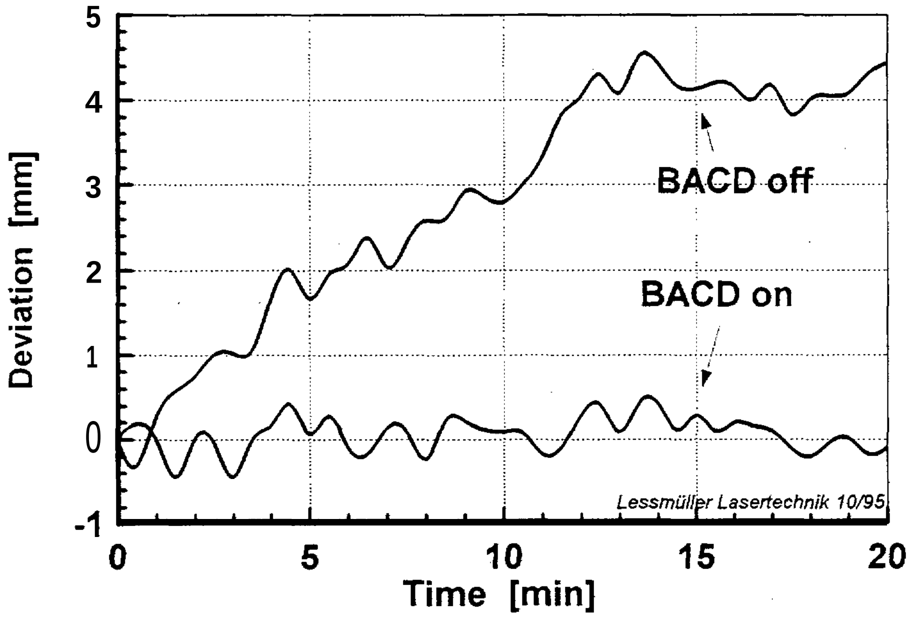

Fig. 8 Beam alignment control on and off. The graph is showing the y-axis at the working head in 41m distance from the laser.

An additional benefit of an automatic alignment control is a reduction in initial set-up time. The long beam path at CETEMA took in excess of 20 minutes to obtain accurate initial alignment using the traditional HeNe and CO_2 approach. This is reduced to 1 minute using the automatic device.

3.3 **Beam Size Control Device (BSCD)**

The beam size control is working within the expected specifications and keeps variations of the beam size within ±1.5%. The response is fast enough to prevent size deviations by thermal lensing effects (see *Fig.* 9).

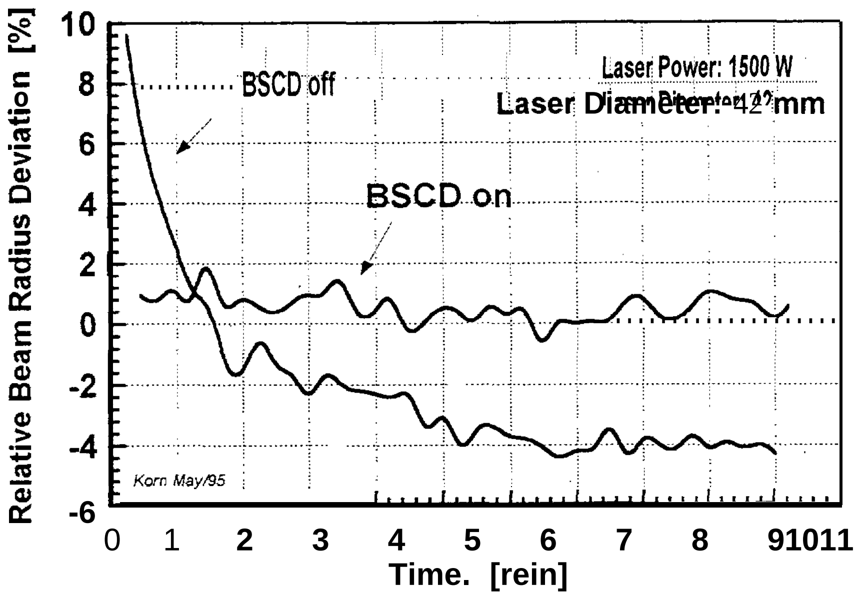

Fig. 9 *Beam size (normalised to the beam size at the beginning) with and without control at the working head in 41m distance from the laser.*

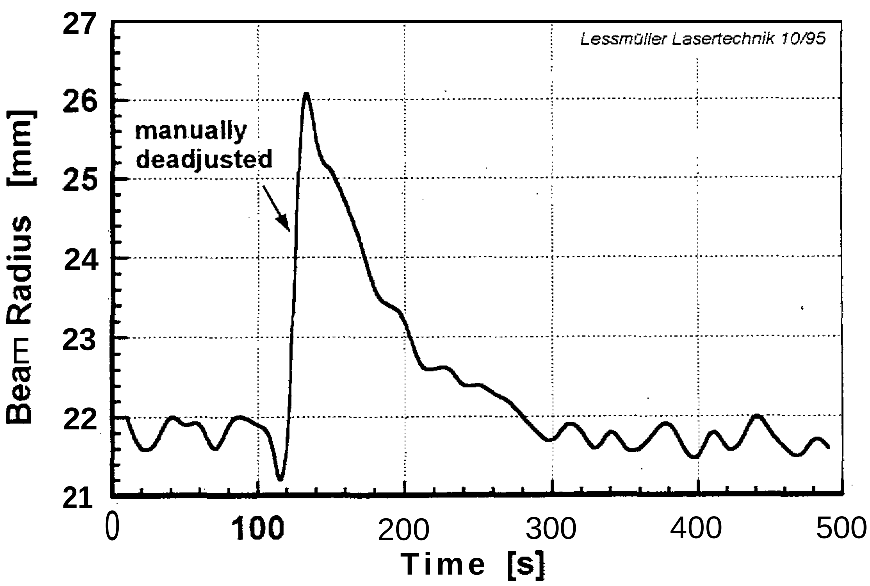

Fig. IO Response of the beam size control to a manual de-adjustment of the telescope.

The response of the size control device to a manual mis-adjustment of the telescope is shown in ***Fig. 10***. It can be seen that the BSCD require 180 seconds to adjust the beam radius to its original size. This time is nearly sufficient for applications with movable optics such as those used in gantries. The speed of adjustment may however be improved during further development.

The telescope operated without any problems within the whole power range of the RS6000 laser and with TEMoo or TEM_{20} mode. During six months of trials, no additional thermal lensing of the telescope itself was observed The telescope is easy to adjust and once installed needs no regular adjustments or maintenance.
Trials with laser power ranging from 1 to 4.6kW showed no astigmatism along the beam path [LLT 3/95]. This demonstrated again the advantage of refractive optics even at high power levels while astigmatism is often a problem when reflective optics are used.

3.4 Performance of the Integrated System

All of the target performance specifications given in the proposal of the BRITE EURAM project could be achieved:

- The pointing accuracy was better than ±0. 5rnm at a distance of 42m [2] (target specification: ±0.5mm at 30m).
- The size could be kept smaller than 60mm all along the beam path under all conditions. The target specification of the diameter stability was ±5% along a beam path of 3 Om and could easily be achieved by keeping the size variations below ±2% **[2].**
- Mode and power repeatability at the remote location was better than ±4% of the power distribution compared to the reference intensity profile.

Three independently developed systems maintaining different beam parameters were integrated into one single system controlled by a common PC. A link to the laser provides data for the integration of the laser into the integrated system. Shutdown procedures were developed and implemented into the control program. These procedures comply with the needs of operator and equipment safety as well as with the requirements of the Flexible System itself.

4 Conclusions

The integrated system has been built and tested very successfully in the long beam path of a laboratory. Further research should therefore directed to the examination of the system in long beam paths while the laser is used for real industrial applications. Further trials of a system installed in a gantry with flying optic should prove the performance and advantage of a fully controlled beam delivery system.

The full integrated system can be seen at the CETEMA site in Madrid, Spain. A stand-alone beam alignment system can be observed at Liverpool University. While in München four separate stand-alone beam mode control devices can be seen operating on different lasers.

This project has successfully generated three new patents [6,7,8] and a potential fourth, it has already produced new business for LLT, ALL & WBL, and promises to lead to new projects and opportunities for Liverpool University, CETEMA and BNFL.

5 Contacts for Further Information

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