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Technical Report
RAL-TR-95-058

The Design and Characterisation of an Optical Imaging System Using f2.5 Aspheric Doublets

R Parker D Neely F N Walsh and C N Danson

October 1995

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Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX.

ABSTRACT

In this report the focusing properties of an f 2.5 aspheric doublet lens are modelled using a commercial raytracing code. The performance of an f 2.5 used in an imaging mode is then investigated. Severe bandwidth limitations lead to the development of an imaging system using a pair of doublets operated in an infinite conjugate ratio. The performance of this system is also studied. Finally, an experiment using the twin doublet imaging system is described, and some images obtained during the course of the experiment are shown.

The Design and Characterisation of an Optical Imaging System Using f2.5 Aspheric Doublets

CONTENTS

1 Introduction

The optical emission generated when high power laser pulses are focused to ultra high intensities (>10^{17} Wcm^{-2}) into gas-jet targets can give important information concerning the size and location of the focal spot and any filamentary structure. An important consideration when using an ultra short pulse (sub ps) high intensity (up to 35 TW) laser beam is the choice of optics used for focusing the beam onto the target. The optical path through transmissive optics must be kept to a minimum in order to conserve beam quality. To minimise this problem, a reflective off-axis parabola (OAP) is used to focus the laser beam. The off axis angle is kept to a minimum, typically 12° → 14° (In order to reduce costs and ease construction). The folded nature of the beam path in such a geometry precludes the use of small, short focal length lenses for diagnostic purposes, as access to the target plane is restricted. To overcome this, an imaging system using existing f2.5 aspheric doublet lenses with a focal length of 0.275 m was designed. With this configuration the lenses and support brackets can be mounted at the opposite side of the beam from the target, without obscuring any of the beam. The system was tested experimentally and produced excellent results[1].

2 Modelling

2.1 Initial lens parameter modelling

The f2.5 doublet lens consists of two fused quartz plano convex lenses. The doublet lens was designed to focus a collimated laser beam to a near diffraction limited spot. Operation at wavelengths between 0.2 and 1 μm is made possible by changing the separation between the elements. The lenses were first used in the early 1980s for focusing a drive laser beam on the VULCAN high power Nd:glass laser to the target plane in an infinite conjugate ratio[2].

To model the focusing properties of the f2.5 doublet it is necessary to specify the shape, refractive index (appendix 1) and location of the surfaces of the lens. The radii of curvature and the design focal length of the doublets were obtained from the original design specification (appendix 2) to simulate the focal spot quality. The shape of the aspheric front element of the doublet was modelled using an optimisation routine of Beam 4[3]. The parameters used in Beam 4 are described in appendix 3. The design focal length was set and the aspheric surface profile optimised (appendix 4) to give the to give the minimum focal spot size. These calculations were made for the f 2.5 doublet, imaging a parallel beam to a point at a wavelength of 527 nm. The centre thickness of the front (aspheric) element is 11 mm and the rear element is 9 mm thick. The refractive index of fused quartz at 527 nm is 1.46092 and the specified back focal length (distance from the last surface of the system to the focal point) of the optic is 274.22 mm. The calculated back focal length is 274.2 mm. The doublet modelled is shown in Figure 1.

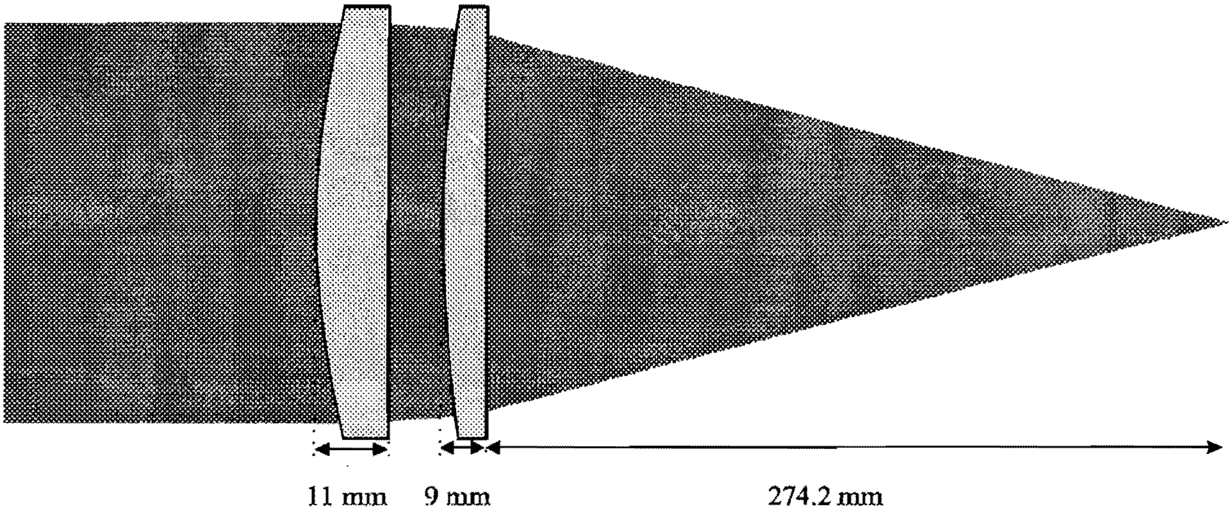


Figure 1. Schematic diagram of the f2.5 aspheric doublet, the front (11 mm) element is asphericised.

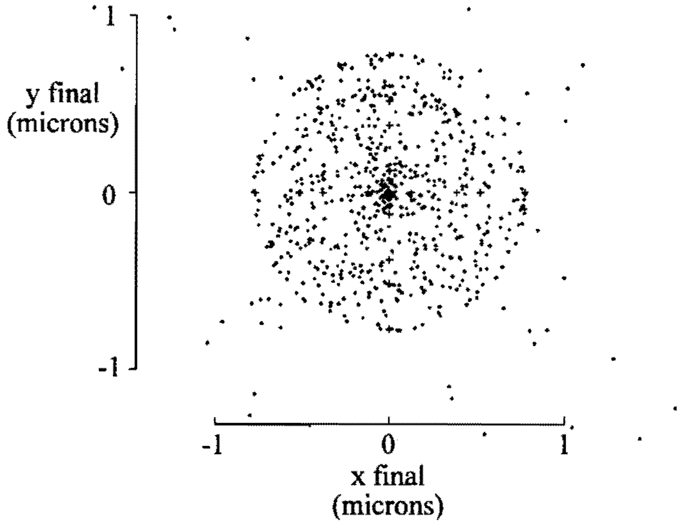


Figure 2. A cross section of the focal spot produced by a single f2.5 aspheric doublet, focusing a parallel beam of wavelength 1054 nm.

The predicted minimum focal spot size produced by a single f2.5 aspheric doublet is shown in Figure 2, focusing a parallel laser beam of wavelength 1054 nm, to a spot. A group of rays in the shape of a cross are used to find the position of the focal plane. Close examination of Figures 2, 3 and 4 reveals this cross as a regular pattern. The other rays seen in Figures 2, 3 and 4 are randomly generated by the program to give an impression of the focal spot shape.

To use the doublet optimally at different wavelengths it is necessary to optimise the separation of the elements, which ranges from 4.88 mm at 1.054 μm to 58 mm at 0.264 μm. The following example shows how critical the separation of the elements is. Using a single doublet to focus a parallel beam of wavelength 1.054 μm to a point, with the element separation optimised for 1.054 μm, the spot size is 1.7 μm, as shown in Figure 2. However, if 0.264 μm light is used at the same separation, the resolution is 54 μm, as shown in Figure 3. Also, if the doublet is reversed, using 1.054 μm light, the resolution increases from 1.7 μm to 1.4 mm, as shown in Figure 4.

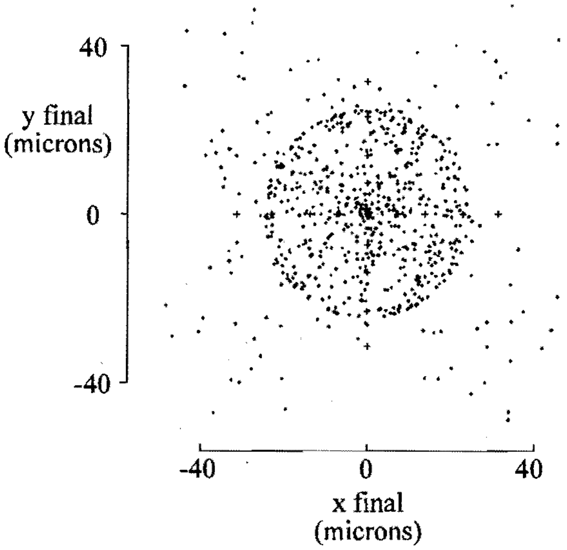


Figure 3. The simulated focal spot produced by a doublet optimised to focus a 1054 nm beam, focusing a 264 nm beam.

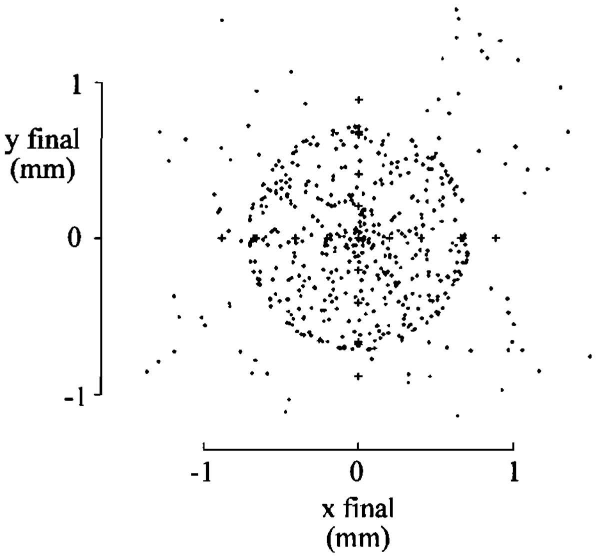


Figure 4. The simulated focal spot produced by a reversed f 2.5 doublet focusing a 1054 nm laser beam.

2.2 Using a single f2.5 doublet for imaging

A high resolution UV imaging system was required to collect scattered laser light from a gas jet target inside a vacuum target chamber and relay the image to an external spectrometer. The target chambers for the Central Laser Facility's high power lasers vary in size from 0.45 to 0.6 m radius. They are under vacuum for each laser shot to stop plasma formation in the beam path, which would prevent the laser beam propagating and focusing to the chamber centre. An imaging system utilising one doublet and a fused silica window was designed to fit into the target chambers, and is shown in Figure 5.

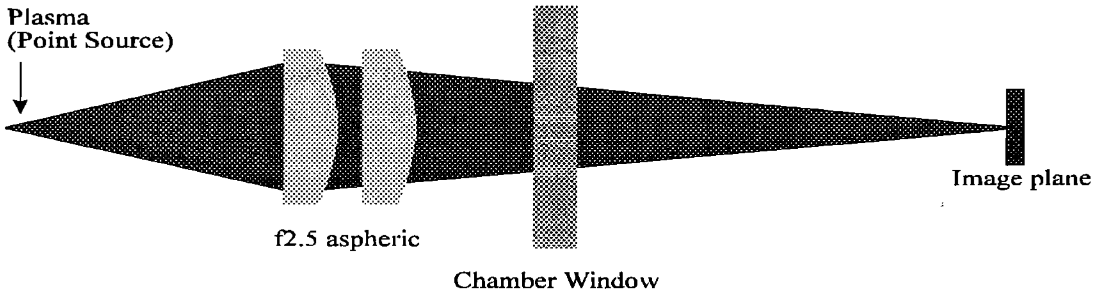


Figure 5. Schematic diagram of the single doublet system used for imaging in the target chamber.

The system was characterised at different magnifications to establish the geometric source resolution as a function of magnification. The imaging system could then be designed around the magnification which gave the best resolution, defined as the diameter of the focal spot, found using Beam 4, divided by the magnification The results are shown in Figure 6.

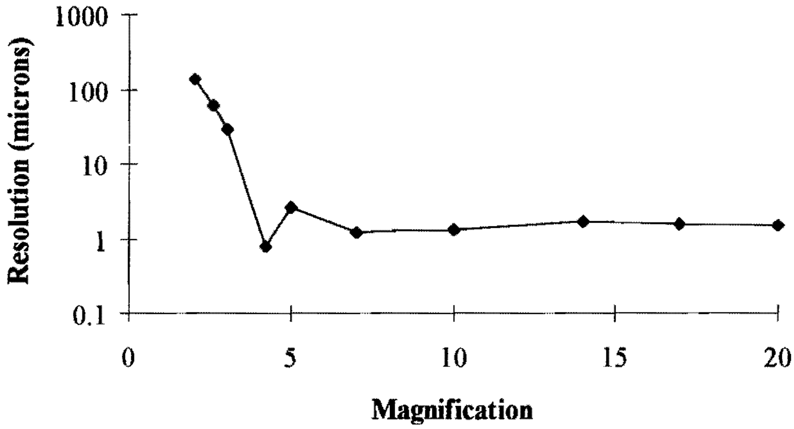


Figure 6. A plot showing how the resolution varies with magnification for a single doublet at 263.5 nm.

The imaging system was raytraced at 1.054 μm, 0.527 μm and 0.264 μm and it was found that the optimum separation of the elements required to image a point to a point was almost identical to that required to focus a parallel laser beam to a point. Figure 7 shows a plot of element separation against magnification for this system.

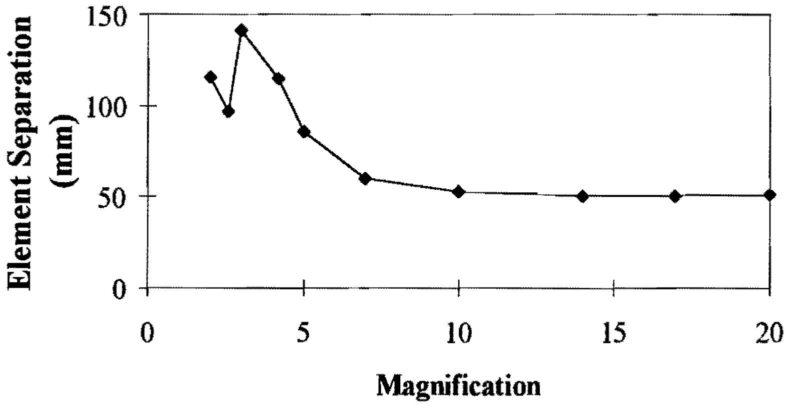


Figure 7. A plot showing how the element separation varies with magnification for a single doublet, operating at 263.5 nm.

The chamber window shown in Figure 5 represents the vacuum-air interface. Adding this component actually improved the calculated resolution of the system, by up to 40%. This effect is caused by the change in refraction experienced by the rays as they pass through the window. The rays furthest away from the optic axis make a greater angle with the window, so they deviate more than rays on or close to the optic axis. See appendix 5 for the Beam 4 optics Table describing this system. Table 1 shows the calculated values of resolution, focal plane distance and element separation for an f 2.5 doublet, imaging a source at 263.5 nm. Some scatter is apparent in the data and this is attributed to the numerical accuracy of Beam 4.

Magnification	Resolution (μm)	Focal Plane Dist. (m)	Element Separation (mm)
2	138	1.281	115.66
2.6	61	1.394	96.49
3	29	1.511	141
4.2	0.8	1.786	115
5	2.6	1.971	85.46
7	1.2	2.439	59.41
10	1.3	3.010	52.43
14	1.7	4.140	50.52
17	1.6	4.698	50.52
20	1.6	6.050	51.03

Table 1. Calculated values for the single f2.5 doublet imaging system

It can be seen from Figure 6 that the resolution is almost constant at around 1.6 μm above x4 magnification. The diffraction limited spot size produced by this lens can be approximated to be NAλ, where NA is the numerical aperture of the optic and λ is the operating wavelength. NA is defined as f/d where f is the focal length of the lens and d is the diameter of the lens. When operating at magnifications other than unity, this is approximated to v/d, where v is the image distance. At 263.5 nm this gives a resolution of 0.7 μm diffraction limited at unity magnification and 0.74 μm resolution at x5 magnification.

One intended use for this system was with the SPRITE gas laser at the Central Laser Facility (CLF), to spatially image scattered radiation from gas jet targets illuminated by UV light onto a spectrometer slit. It is therefore necessary to maintain good resolution over a 50 nm range of wavelengths. A discussion of the spectral bandwidth (the range of wavelengths brought to a tight focus in the same plane) limitations now follows:

To a first order approximation the focal length, f, of the doublet can be related to the refractive index, η, as shown in equation (1), where k is a constant which depends on the separation of the lenses and their radii of curvature. (for 263.5 nm, the UV wavelength at which the system would be operated, $k = 0.121$ m.)

$$f = k(\eta - 1)^{-1} \qquad (1)$$

The refractive index η of fused silica for wavelengths between 0.2 and 1.2 microns can be approximated to:

$$\eta = a + b\lambda^{-2} \qquad (2)$$

where $a=1.44659$ and $b=-3.81\times10^{-15}\text{m}^2$.

Differentiating, we obtain:

$$\frac{d\eta}{d\lambda} = -2b\lambda^{-3} = \frac{-2b}{\lambda^3} \qquad (3)$$

The equation relating image distance to object distance for a simple lens (appendix 6) is:

$$\frac{1}{u} + \frac{1}{v} = \frac{(\eta - 1)}{k} \qquad (4)$$

where f is the focal length.

Differentiating (4) we obtain:

$$-u^{-2}\frac{\partial u}{\partial \eta}-v^{-2}\frac{\partial v}{\partial \eta}=\frac{1}{k} \qquad (5)$$

setting $\frac{\partial u}{\partial \eta}$ to zero (the image distance is fixed) gives:

$$\Delta v=\frac{v^2}{k}\Delta\eta \qquad (6)$$

combining (3) and (6) we obtain:

$$\Delta v \cong \frac{-2bv^2}{k\lambda^3}\Delta\lambda \qquad (7)$$

It is therefore clear that for shorter wavelengths, the change in position of the focal plane, Δv, is greater than for longer wavelengths.

The depth of focus, D, can be equated to:

$$\lambda/2(\mathrm{NA})^2 \qquad (8)$$

where NA is the numerical aperture of the system, given by v/d where d is the diameter of the optic. It can therefore be shown that to a first order approximation for a given wavelength λ, the bandwidth of the system $\Delta\lambda$ is given by:

$$\Delta\lambda=\frac{k\lambda^4}{-4bd^2} \qquad (9)$$

which at $\lambda = 263.5$ nm gives $\Delta\lambda = 3.2$ pm

Since the bandwidth is so small, a commercial achromatic lens was purchased to replace the doublet for the SPRITE application.

2.3 Imaging with two f2.5 doublets

The imaging properties of a system consisting of two doublets placed opposite each other in an infinite conjugate ratio were investigated. This system is shown in Figure 8.

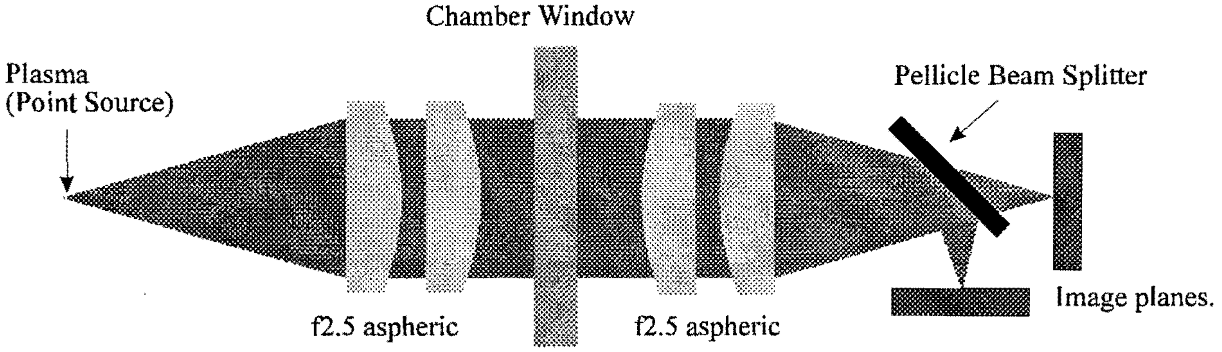


Figure 8. Schematic of the twin doublet imaging system.

The imaging system shown in Figure 8 was initially set up for operation at the second harmonic (λ=527 nm), and was ray-traced accordingly. When the centres of the adjacent lens surfaces are 17.9 mm apart (the optimised distance) the calculated resolution is 3 μm. When the beam passes through the chamber window shown in Figures 5 and 8, it is parallel and no noticeable effect is made upon the calculated resolution.

The imaging system was also required to be used at infra-red wavelength (λ=1054 nm) and green (λ=527 nm) simultaneously. The ray-tracing showed that with the element separation for 1054 nm (4.88 mm) it was possible to image 527 nm with a resolution of 6 μm, providing the detector plane is moved 14 mm further from the lens. For a given wavelength it is therefore possible, using a combination of bandpass filters and pellicle beam splitters, to image multiple wavelengths simultaneously onto multiple CCD detectors, although the resolution for wavelengths other than that for which the doublets are optimised will be reduced. Figure 9 shows a schematic of the imaging system in Target Area West (TAW).

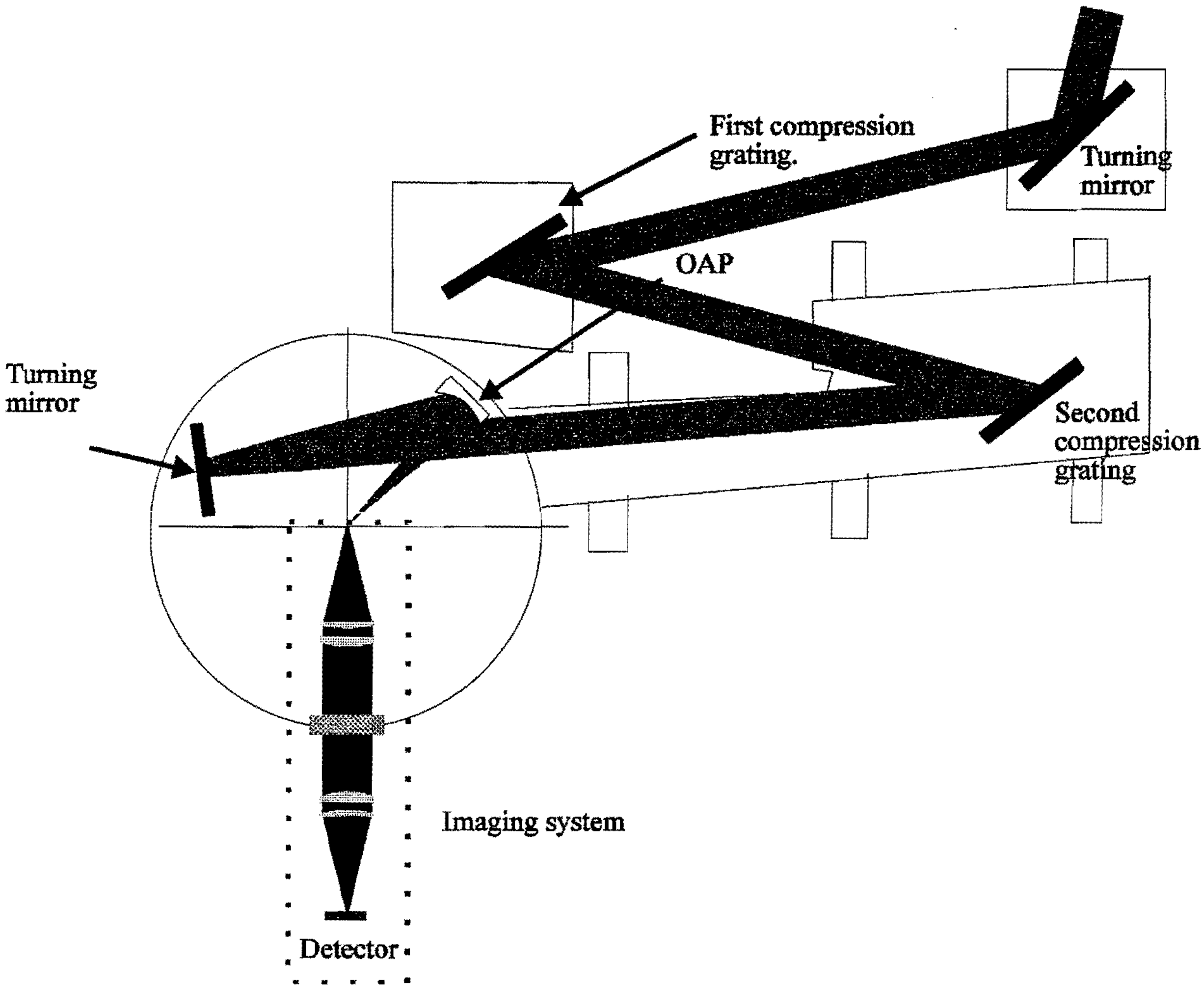


Figure 9. Schematic diagram of the twin doublet imaging system, within the TAW chamber, showing the position of the laser beam and off axis parabola (OAP).

3 Experimental Results

3.1 Introduction

An experiment[5] to accelerate electrons trapped in plasma waves generated by Self-Resonant Wakefield and Forward Raman Scattering, to 44 MeV, was conducted in TAW, by groups of experimenters from Imperial College, London; UCLA, Los Angeles; Ecole Polytechnique, France; LLNL Livermore, USA and Rutherford. The experiment was conducted using the VULCAN CPA (Chirped Pulse Amplified)[4] 1 μm laser, which is capable of delivering 25 J in a 0.7 pulse to target. The laser power had a typical value of 25 TW and a focused intensity of $5\text{x}10^{18}$ Wcm^{-2}. The laser was focused onto the edge of a plume of gas (helium or hydrogen) from a gas jet target. The gas jet had a small brass nozzle 4 mm in diameter and was connected to a fast switching valve. The gas was travelling at supersonic speeds, with a backing pressure ranging from 5 to 18 bar. The valve opened for a few ms immediately prior to the laser shot, this prevents the chamber from becoming filled with gas which would stop propagation of the beam to target. The laser was focused 2 mm above the gas jet. The maximum intensity of the beam was sufficient to doubly ionise the helium over a length of 2 mm into the jet. Due to the high intensity, large amounts of second harmonic was produced (conversion efficiency of $\sim10^{-3}$) which was measured both spectrally, in the forward direction and onto a CCD camera at 30^0.

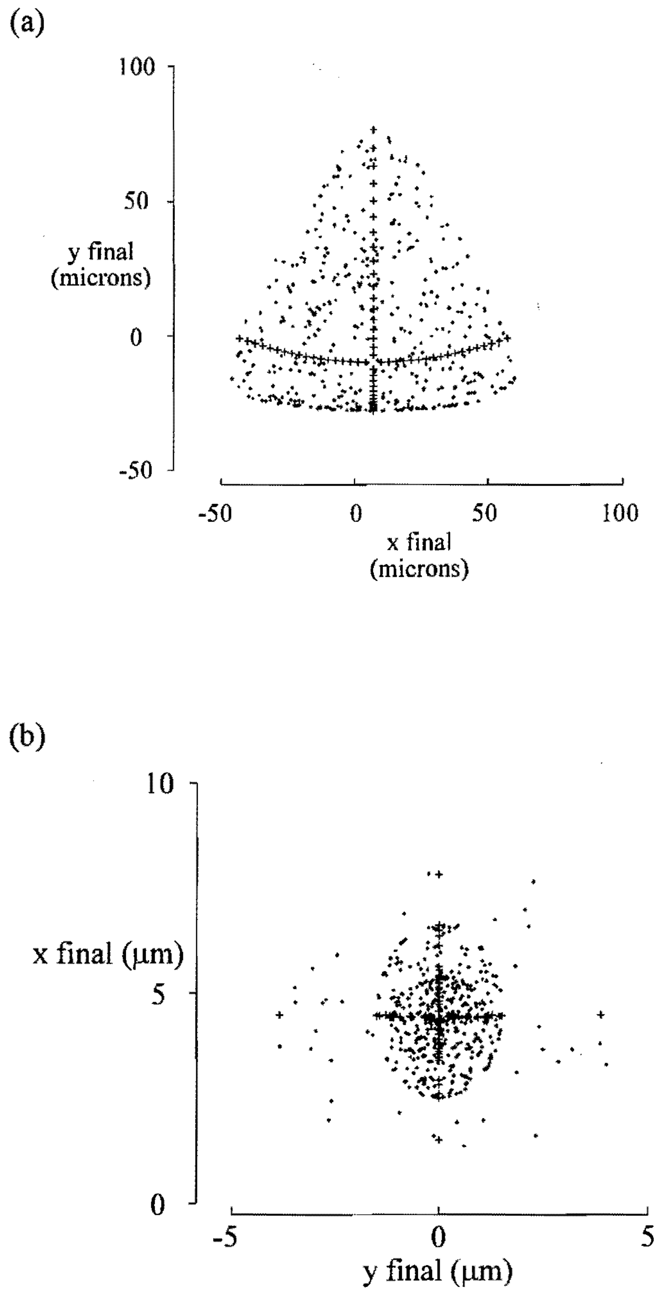
The experiment required that the focal plane be viewed at two magnifications simultaneously. At a low magnification to get an overall view of the gas jet and at high magnification to view just the initial laser / gas interaction area. Later, during the experiment, it became desirable to image both the fundamental and the second harmonic simultaneously. These requirements were achieved using a beamsplitter.

3.2 Experimental set up

To produce two images simultaneously as described earlier, a beamsplitter is required. If a standard dielectric mirror (5 mm thick) is employed for this purpose, the amount of beam distortion that occurs when passing through 7 mm (the splitter is at 45 degrees) of fused silica degrades the resolution to 120 μm. If a 20 μm thick pellicle beamsplitter is used there is insignificant beam degradation (the resolution is 3.4 μm.)

To correctly image the fundamental and second harmonic simultaneously, A micro-balloon of diameter 50 μm is used as a reference sphere positioned where the gas jet would be located. The sphere is illuminated by laser light of the appropriate wavelength and the CCD cameras are moved until the position of optimum focus is found. A bandpass filter is placed in front of each camera to prevent all wavelengths other than those of interest from saturating the image.

Figure 10a shows the simulated focal spot obtained with a mirror as a beamsplitter, and Figure 10b shows the simulated focal spot, using a pellicle beamsplitter, both at 1054 nm.



Figures 10a and 10b. a) The simulated focal spot if a mirror is used as a beamsplitter and b) if a pellicle is used. The splitter is 200 mm from the rear surface of a double f 2.5 system, imaging at 1054 nm.

The initial rays used to calculate the focal plane position are clearly visible in figure 10a. When multiple wavelengths are imaged simultaneously the resolution and position of the focal plane is different for each wavelength (since the element separation is fixed). These changes are shown in

Table 2. The resolution obtained for the twin doublet system with the element separation individually optimised for wavelength is shown in Table 3

Wavelength (nm)	Resolution (μm) optimised for 1054 nm	Resolution (μm) optimised for 527 nm	f [1054 nm] (mm)	f [527 nm] (mm)
263	81	58	225.6	205.6
400	46	51	254.9	237.5
527	20	4	275.6	258.0
632	13	7	279.3	263.2
1054	3	34	288.5	272.8

Table 2. The calculated results for the twin doublet imaging system, with the element separation optimised for 1054 nm and 527 nm. (f = focal plane distance from rear surface of system)

Wavelength (nm)	Resolution (μm)
263	2.3
400	4.0
527	3.75
632	2.8
1053	3.0

Table 3. Individually optimised resolution results for the twin doublet imaging system.

3.3 Experimental results

The imaging system consisting of a pair of doublets was used to image the harmonic emissions from several gas jet targets. The second harmonic was emitted in all directions, and was imaged at 30^0 onto a CCD. Two typical images are shown in Figures 11 & 12. The Helium image shows some especially interesting features in the shape of filamentation, which extends much further than the Raleigh length. (In this case 300-350 μm)

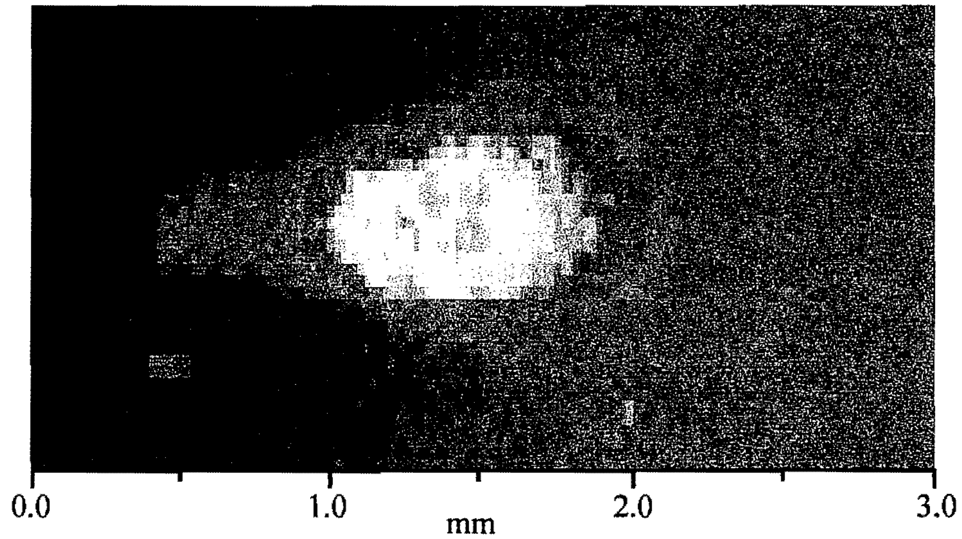


Figure 11. Image obtained with the twin doublet system, imaging the 2nd harmonic emission from hydrogen.

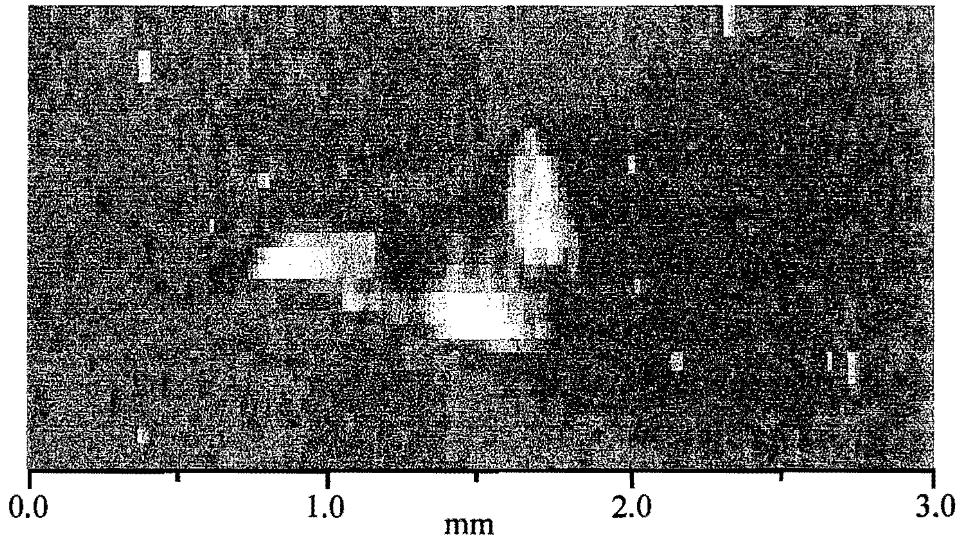


Figure 12. Image obtained with the twin doublet system, imaging the 2nd harmonic emission from helium.

These images were obtained using a computer controlled 8-bit framestore and a Pulnix TM500 CCD television camera. The camera has a 256x512 array of pixels, with a pixel size of approximately 8.6 µm x 8.3 µm. To obtain the high resolution (4 µm or better) on a detector whose resolution is 8 µm, it is necessary to magnify the image using a microscope objective in front of the CCD camera. The colour is artificial and has been added to enhance the image.

4 Conclusion

The imaging system consisting of a single doublet was found to be inapropriate for spectral imaging, which had been the primary objective for it. An imaging system using a pair of f2.5 doublets has been used successfully in Target Area West several times and has achieved the required resolution. There are plans to develop the system further, by introducing a grating or prism between the two doublets, thereby creating a 2D spectrometer.

5 Acknowledgements

We would like to thank Z. Najmudin of Imperial College, London, for allowing us to present the images shown in Figures 11 and 12.

6 References

1. Z. Najmudin et al., 1994/5 Central Laser Facility Annual Report, p34
2. Optics (2nd ed.), Hecht, Addison-Wesley Publishing Co., 1987 p190-194
3. Beam 4, 1988 Stellar Software, PO Box 10183, Berkeley, CA 94709
4. P. Maine et al., SPIE Vol. 913 (1988) p140
5. A. E. Dangor et al., submitted to Nature, 1995
6. Ealing Electro Optics Catalogue, 1994, p165,167

APPENDIX 1

Refractive index

The refractive index of fused silica and BK7 are given by equations (11) and (12) respectively[6]

$$\frac{A_0\lambda^2}{\lambda^2-B_0}+\frac{A_1\lambda^2}{\lambda^2-B_1}+\frac{A_2\lambda^2}{\lambda^2-B_2}+1=n^2 \qquad (11)$$

where A_0=0.6961663	A_1=0.4079426	A_2=0.8974794
B_0=0.004679148	B_1=0.01351206	B_2=97.934003

and λ is the wavelength in microns.

$$n^2=A_0+A_1\lambda^2+A_2\lambda^{-2}+A_3\lambda^{-4}+A_4\lambda^{-6}+A_5\lambda^{-8} \qquad (12)$$

where: A_0=2.2718929x10^0	A_1=-1.0108077x10^{-2}	A_2=1.0592509x10^{-2}
A_3=2.0816965x10^{-4}	A_4=-7.6472538x10^{-6}	A_5=4.9240991x10^{-7}

A plot of each of these refractive indices is shown in Figure 13.

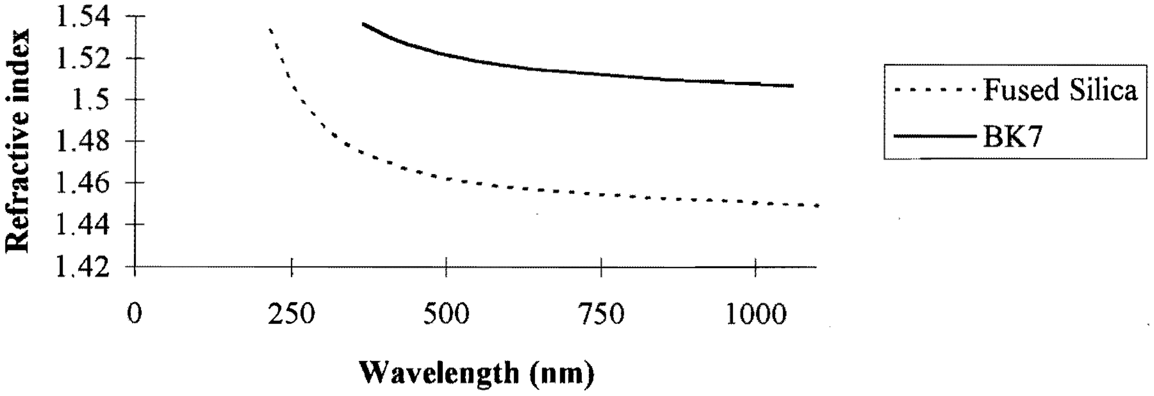


Figure 13. A plot showing how the refractive indices of fused silica / quartz and BK7 changes with wavelength.

APPENDIX 2

Design specifications for the f2.5 aspheric doublets

The following are the manufacturers details and should be used in conjunction with drawing 1R145676, shown overleaf.

Lens Type :	Doublet consisting of two plano-convex lenses of approximately equal power.
Material :	Fused synthetic quartz - Spectrosil 'B' or equivalent.
Working aperture :	110 mm with specification applying over the central 100 mm.
Back focal length :	275 mm at 546 nm.

Design to give the specified performance at the following wavelengths using different lens spacings (t) : 1060 nm, 633 nm and 527 nm. Spacings maximum at longest wavelengths.

1^{st} and 2^{nd} order ghosts to lie outside lens material.

Asphericised by hand to give minimum wavefront aberration, (better than $\lambda/4$ @ 632.8 nm with gradients less than $\lambda/4$ cm^{-1} @ 632.8 nm).

Edges fine ground and corners chamfered 0.5 mm, 45°.

Very best high quality polish, free from scratches and digs better than 10/5.

Each lens is to be marked to show a unique serial number.

Each lens shall be individually wrapped in chemically inert paper that will not scratch, leave a residue or corrode the lens surface.

The wrapped lens shall be immobilised in a unit container that provides adequate protection during handling and shipment.

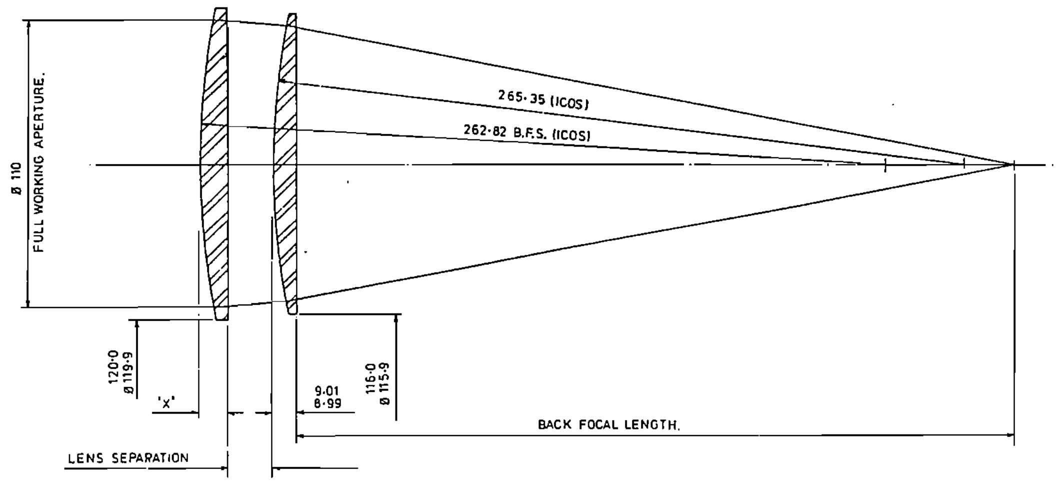
Shipping containers shall be marked with the words "DELICATE OPTICAL COMPONENTS REQUIRING SPECIAL HANDLING. ONLY TO BE OPENED BY TECHNICAL PERSONNEL FAMILIAR WITH THE NATURE OF THE CONTENTS"

1R145676

PROJECTION

THIS DRAWING CONFORMS TO B.S.308

LIGHT SOURCE	WAVE LENGTH(nm)	REFRACTIVE INDEX FOR SPECTROSIL	INTERMEDIATE MEDIUM	OPTIMUM COMP. SEPARATION (mm)	BACK FOCAL LENGTH (mm)
Nd/GLASS LASER	1054·0	1·44972	VACUUM	5·34	284·58
Nd/GLASS LASER	1054·0	1·44972	AIR.	4·88	284·95
He/Ne LASER	632·8	1·45699	VACUUM	13·60	277·80
He/Ne LASER	632·8	1·45699	AIR.	13·11	278·18
MERCURY GREEN*	546	1·46005	VACUUM	17·00	275·00
MERCURY GREEN	546	1·46005	AIR.	16·52	275·38
SECOND HARMONIC GREEN.	527	1·46092	VACUUM	17·93	274·22
SECOND HARMONIC GREEN.	527	1·46092	AIR.	17·48	274·59
THIRD HARMONIC BLUE.	351	1·47671	VACUUM	34·76 †	260·29
THIRD HARMONIC BLUE.	351	1·47671	AIR.	34·32 †	260·66
FOURTH HARMONIC NEAR U.V.	263·5	1·50079	VACUUM	57·87	240·61
FOURTH HARMONIC NEAR U.V.	263·5	1·50079	AIR.	57·47	[illegible]



'X' TO BE
- 11·20 / 11·10 AFTER INITIAL GRINDING TO BEST FIT SPHERE.
- 11·01 / 10·95 AFTER FINAL FIGURING AND POLISHING TO ASPHERIC PROFILE

NOTES.

- * DESIGN WAVELENGTH
- † A SEPARATION OF 22mm WOULD BE SUFFICIENT IN PRACTICE.

FOR LENS HOLDER SEE DRG. Nº 1R186151

MATERIAL & SPEC.
FUSED SYNTHETIC QUARTZ SPECTROSIL 'B'
REMOVE ALL BURRS

TOLERANCES UNLESS STATED

DRN R. DAY.
CHKD
APPD
FINISH
SURFACE TEXTURE µm
✓ UNLESS STATED
ORIGINAL SCALE 1:1
0 50 mm.
INCHES

1R145676

JOB No.
PROJ. No.
USED ON

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Science & Engineering Research Council
RUTHERFORD AND APPLETON LABORATORIES CHILTON

TITLE
F2·5 ASPHERIC DOUBLET LENS

CONTR'S REF

1R 145676

APPENDIX 3

The Beam 4 parameters

The optical surfaces in the Beam 4 program had 6 parameters, refractive index (Index) (see appendix 4), position on optic (horizontal) axis (Zvx), Curvature (Curv), a description (Mir/Lens), the diameter and the shape.

The following two descriptions are taken from the Beam 4 manual:

CURVATURE or CURV is the reciprocal of the radius of curvature, and takes a value of zero if the surface is flat.

SHAPE is defined as 1.00 minus the square of the conic section that generates the surface:

shape<0.0	hyperboloid
shape=0.0	paraboloid
0<shape<1	prolate ellipsoid
shape=1.0	sphere
shape>1.0	oblate ellipsoid

The mathematical description of these surfaces having shape = s is:

$$\frac{cr^2}{1+\sqrt{1-sc^2r^2}} = z \qquad \text{where } r=\sqrt{x^2+y^2} \qquad (10)$$

It should be noted that in the Optics Tables, a piece of glass such as a window is described as a lens, but with an infinite radius of curvature. This can be seen in Tables 6 and 7 found in appendix 5.

APPENDIX 4

Beam 4 parameters for the f2.5 aspheric doublet

Table 4 shows the optical paramenters inserted into the Optics Table of Beam 4, used for the initial parameter modelling and optimisation of the aspheric shape of the lens. As can be seen from Table 4, the f2.5 aspheric doublets used in the imaging systems had only one aspheric element, the 11 mm thick front one. The rear, 9 mm thick element was a simple spherical lens. Appendix 3 has information on the Beam 4 parameters.

Index	Zvx	Curv	Mir/Lens	Diameter	Shape
1.000	0.00000		Iris	0.110	
1.000	0.27500	3.79310	Lens	0.110	-0.36866
1.46092	0.28600	0.00000	Lens	0.110	
1.000	0.30393	3.76861	Lens	0.110	
1.46092	0.31293	0.00000	Lens	0.110	
1.000	0.58715		Film		

Table 4. The optics Table from Beam 4 using a single f2.5 doublet to image a parallel beam to a point at 527 nm.

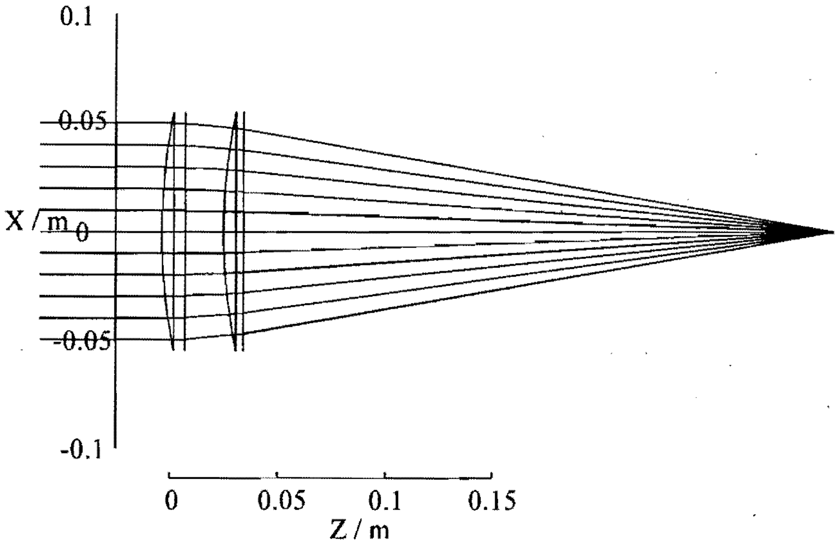

Figure 14. Schematic of the f2.5 doublet focusing a parallel beam to a point.

Figure 14 is a schematic diagram of the system described by the optics Table above, being used to focus a parallel laser beam (λ=527 nm) to a point, in order to optimise Curv and Shape. The optimised values for element separation and focal plane distance (back focal length) of the doublet at five wavelengths of interest are shown in Table 5.

Wavelength (nm)	Refractive Index of Fused Silica	Element Separation (mm)	Focal Plane Distance (m) wrt. rear surface of lens
263	1.50079	68.82	0.24522
400	1.47672	30.03	0.24937
527	1.46092	17.93	0.27459
632	1.45699	13.56	0.27744
1053	1.44972	6.53	0.28304

Table 5. showing the optimised parameters for the doublet.

A plot of the focal plane distance from the rear surface of the system operated at an infinite conjugate ratio is shown in Figure 15. The doublet was optimised for each individual wavelength.

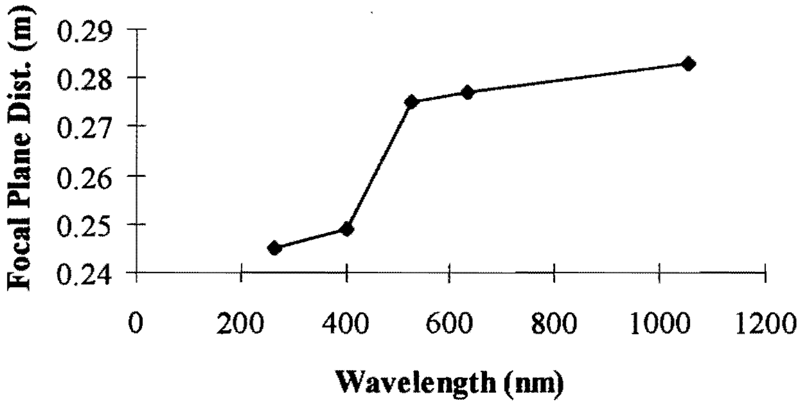

Figure 15. Plot showing the position of the focal plane, with respect to the rear element of the system operating at an infinite conjugate ratio.

APPENDIX 5

The Beam 4 Optics Tables for the imaging systems

Index	Zvx	Curv	Mir/Lens	Diameter	Shape
1.000	0.000		Iris	0.110	
1.000	0.26468		Lens	0.110	
1.50079	0.27368	-3.76861	Lens	0.110	
1.000	0.32420		Lens	0.110	
1.50079	0.33520	-3.7931	Lens	0.110	-0.36866
1.000	0.58		Lens	0.110	
1.50079	0.595		Lens	0.110	
1.000	3.0079		Film		

Table 6. The optics Table for the single doublet system operating at 264 nm and at x10 magnification.

Index	Zvx	Curv	Mir/Lens	Diameter	Shape
1.000	0.000		Iris	0.110	
1.000	0.27321	0.000	Lens	0.110	
1.46092	0.28221	-3.76861	Lens	0.110	
1.000	0.30014	0.000	Lens	0.110	
1.46092	0.31114	-3.7931	Lens	0.110	-0.36866
1.000	0.6	0.000	Lens	0.120	
1.5	0.62	0.000	Lens	0.120	
1.000	1.2	3.7931	Lens	0.110	-0.36866
1.46092	1.211	0.000	Lens	0.110	
1.000	1.22848	3.76861	Lens	0.110	
1.46092	1.23748	0.000	Lens	0.110	
1.000	1.51308		Film		

Table 7. The optics Table for the twin doublet imaging system, at λ=527 nm and at unity magnification.

APPENDIX 6

Basic lens theory

The term f2.5 describes an optic with a ratio of focal length to diameter of 2.5. In this case, the focal length of the doublet is 0.275 m and the diameter is 0.11 m. The ratio is therefore 0.275/0.11, which is 2.5. In general, most lenses have a radius of curvature, which is the distance shown in Figure 16, below.

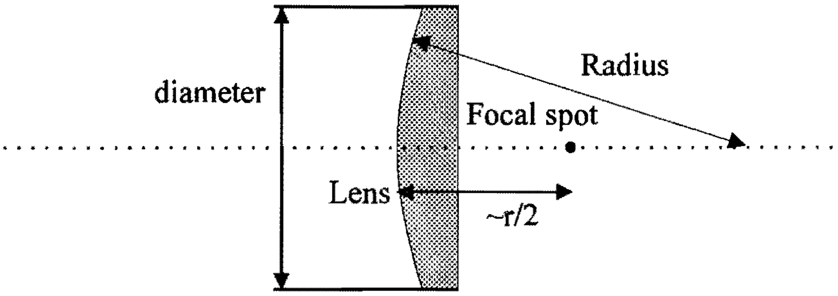

Figure 16, Schematic of a simple lens.

The radius, r, is the distance to a point about which the lens may be rotated on the optic axis, (shown in Figure 7 as a dotted line) without changing the point of focus. Taking the case of a simple, plano convex lens, r is related to the focal length, f, and the refractive index, η, as follows:

$$\frac{1}{f}=(\eta-1)\left(\frac{1}{r_1}-\frac{1}{r_2}\right)+\frac{(\eta-1)^2 C_T}{\eta r_1 r_2} \qquad (13)$$

where C_T is the centre thickness of the lens.

In the plano convex case, r_1 is the radius of the plano side of the lens and is infinite, so the relationship simplifies to:

$$\frac{1}{f}=\frac{(\eta-1)}{-r_2} \qquad (14)$$

In the case of an aspheric optic, the curved surface has been reshaped to give optimum focusing of a parallel beam to a point, and therefore the radius is not constant over the whole surface. r_2 is the value of the radius for the curved side of the lens. In Beam 4, a positive value for r_2 indicated that the lens was oriented as shown in Figure 14 (appendix 3), with the curved surface towards the input beam. Conversely, if the value of r_2 is negative, the lens is reversed.

A doublet lens simply has two optical elements. Achromatic lenses have at least two elements, with each element made from materials with different refractive indices, so that light of different wavelengths is brought to a focus at the same point. Achromats are not used in these imaging systems due to the large amount of reshaping involved in a lens of this size.