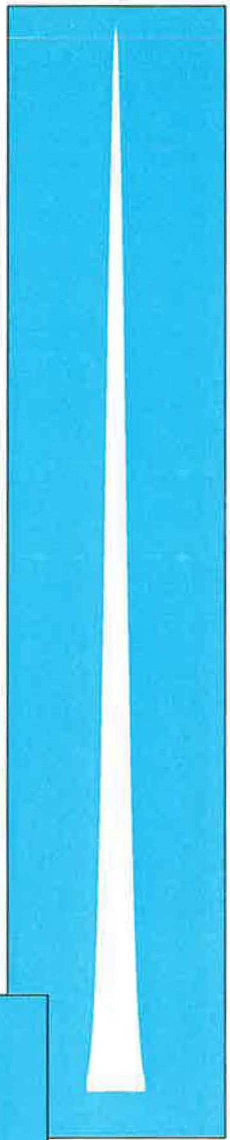
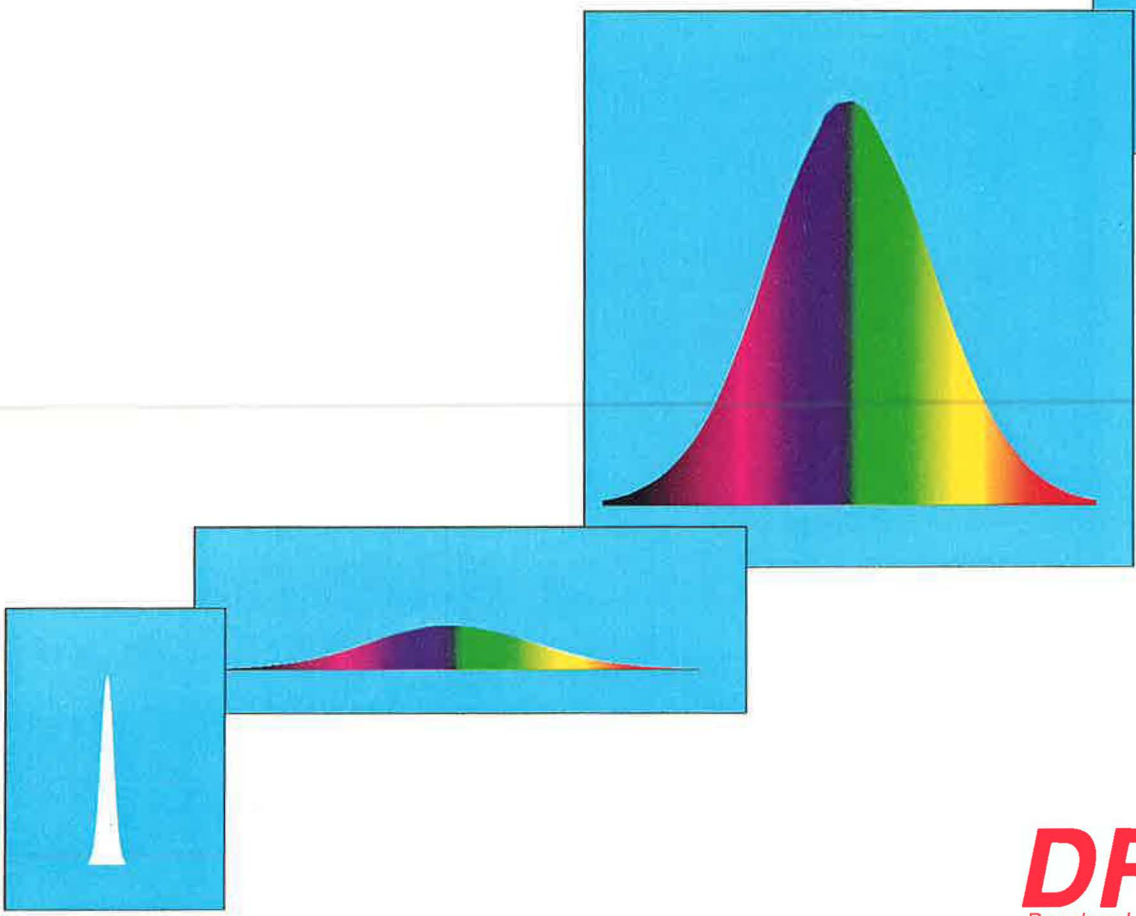
RAL Report No 94059



RAL High Power Laser Facility Enhancements

Joint Projects Final Report

Rutherford Appleton Laboratory
Imperial College, London
University of Southampton
University of St Andrews



DRAL
Daresbury Laboratory
Rutherford Appleton Laboratory

RAL High Power Laser Facility Enhancements

Joint Projects Final Report

RAL Report No 94059

M H Key, S Angood, L J Barzanti, A R Damerell, C N Danson, E J Divall,
K N Drodge, M D Ebbage, C B Edwards, M J Gander, J Govans,
S Hancock, G J Hirst, C J Hooker, J R Houliston, A K Kidd,
J M D Lister, R Mahadeo, D Neely, P Norreys, D A Pepler,
S A Rivers, D A Rodkiss, I N Ross, M J Shaw, M Smith,
P Taday, W T Toner, T B Winstone, F N Walsh, K Wigmore,
R W W Wyatt and B Wyborn
Central Laser Facility, Rutherford Appleton Laboratory

M H R Hutchinson, S Luan, I P Mercer, G H C New, R A Smith,
D C Wilson and F Zhou
Blackett Laboratory, Imperial College, London

J R M Barr, D C Hanna, D W Hughes and A Majdabadi
Optoelectronics Research Centre
Southampton University

J M Evans and W Sibbett
University of St Andrews

K Osvay
JATE University, Hungary

Z Chang
Xian Institute of Optics, Peoples Republic of China

Summary

This report describes the 2 year Joint Project undertaken by the Central Laser Facility, the University of St Andrews, Southampton ORC and Imperial College to enhance the performance of high power lasers at the CLF. Three projects were undertaken:

- Chirped Pulse Amplification (CPA) on the Vulcan Glass Laser (Imperial College and Southampton)
- Sub-Picosecond CPA Pulses on the Sprite KrF Laser (St Andrews)
- Enhancement of the Sprite Raman Beam (Imperial College).

The projects were outstandingly successful, resulting in very significant improvements in the capabilities of the high power lasers at the CLF. This work places the CLF as a world leader in high brightness laser facilities. The stimulus given to UK expertise in the field of short pulse, high power lasers is an important spin-off from this initiative.

The application of the CPA technique to Vulcan has raised the performance to 35 TW in a pulse duration of 620 fs. An irradiance on target of 10^{19} W cm^{-2} at $\lambda = 1.05$ µm has been obtained, enabling experiments in the relativistic regime to be performed for the first time. A pulse-to-background contrast ratio of better than 3×10^6 has been measured.

Sub-picosecond output has been obtained from Sprite using CPA. This is the first time that the technique has been applied to a UV laser. A power of 1 TW has been delivered to target in a pulse of 290 fs duration. Focused irradiance at 10^{19} W cm^{-2} at $\lambda = 248$ nm has been obtained and made available to users.

The enhancement of the Sprite Raman beam has doubled the power on target to 1 TW at a pulse duration of 10 ps. The maximum energy has increased from 5 J to over 13 J at a pulse duration of 25 ps. This unique prepulse-free beam can be focused to a near diffraction limited spot, producing 10^{19} W cm^{-2} irradiance at $\lambda = 268$ nm establishing Sprite at the forefront of high brightness laser facilities.

These new facilities have provided experimenters at the CLF with unique capabilities for the study of laser interaction with matter at extreme intensity. Exploitation of these opportunities has been rapid and exciting leading to many topical publications from user groups and RAL staff. Appendix A lists in press and published material. Many invited papers and other conference presentations arose from this work.

RAL High Power Laser Facility Enhancements

Joint Projects Final Report

DRAL Report No 94059

M H Key, L J Barzanti, A R Damerell, C N Danson, M D Ebbage, C B Edwards,
M J Gander, S Hancock, C J Hooker, J R Houliston, A K Kidd, D Neely, P Norreys,
D A Pepler, S A Rivers, D A Rodkiss, I N Ross, M J Shaw, P Taday, W T Toner,
T B Winstone, F N Walsh and R W W Wyatt
Central Laser Facility, Rutherford Appleton Laboratory

M H R Hutchinson, S Luan, I P Mercer, G H C New, R A Smith,
D C Wilson and F Zhou
Blackett Laboratory, Imperial College, London

J R M Barr, D C Hanna, D W Hughes and A Majdabadi
Optoelectronics Research Centre
Southampton University

J M Evans and W Sibbett
University of St Andrews

K Osvay
JATE University, Hungary

Z Chang
Xian Institute of Optics, Peoples Republic of China

Summary

This report covers Joint Projects approved by Science Board between The Central Laser Facility and The Universities of St Andrews, Southampton and Imperial College for the purpose of enhancing the performance of RAL's high power lasers.

The projects ran for two years (92-94) with a budget of £750k.

Three projects were undertaken:

- Chirped Pulse Amplification (CPA) on the Vulcan Glass Laser (Imperial College and Southampton)
- Sub-Picosecond CPA Pulses on the Sprite KrF Laser (St Andrews)
- Enhancement of the Sprite Raman Beam (Imperial College).

This collaboration was most successful, being completed close to time and budget and leading to very significant improvements in the capabilities of the high power lasers at the CLF. These improvements place the CLF as **the World leader** in high brightness laser facilities. The stimulus given to UK expertise in the field of short pulse, high power lasers is an important spin-off from this initiative.

The application of the CPA technique to Vulcan has raised the performance to 35 TW in a pulse duration of 620 femtosecs. An irradiance on target of 10^{19} W cm^{-2} at $\lambda = 1.05$ µm has been obtained which has permitted experiments in the relativistic regime to be performed for the first time. A pulse-to-background contrast ratio of better than 3×10^6 has been measured.

Sub-picosecond output has been obtained from Sprite using CPA, the first time this technique has been applied to a UV laser. A power of 1 TW has been delivered to target in a pulse of 290 femtosecs duration. Focussed irradiance upto 10^{19} W cm^{-2} at $\lambda =$ 248 nm has been obtained and made available to users.

The enhancement of the Sprite Raman beam has doubled the power on target to 1 TW at a pulse duration of 10 ps. The maximum energy has increased from 5 J to over 13 J at a pulse duration of 25 ps. This unique prepulse-free beam is capable of being focussed to a near diffraction limited spot of 10^{19} W cm^{-2} irradiance at $\lambda = 268$ nm, putting Sprite at the forefront of high brightness lasers in the world.

These diverse high brightness laser facilities have provided experimenters at the CLF with unique capabilities for the study of laser interaction with matter at extreme intensity. Exploitation of these opportunities has been rapid and exciting.

The work undertaken during the joint projects has led to many topical publications from both the university groups involved and RAL staff. Appendix A gives a list of the published and 'to be published' material. A large volume of invited papers and other unpublished conference presentations also arose from this work.

RAL High Power Laser Facilities Enhancements

Joint Projects Final Report

1. Background

In 1992 the Science Board approved an additional bid from the Central Laser Facility to enhance the High Power Laser capabilities at the CLF. This objective was to be achieved by establishing a series of Joint Projects with various University groups who would bid for contracts monitored by CLF staff. The projects were to run a maximum of two years (FY 92/93-FY93/94) with a budget of £750k.

Three projects were identified which would significantly enhance the existing facilities. These were:

1. Chirped Pulse Amplification(CPA) on the Vulcan glass laser
2. Sub-Picosecond Pulses on the Sprite KrF laser
3. Enhanced Raman Beams on Sprite.

Four contracts were let to university groups. Professor Hanna's group at Southampton University for the development of new short pulse oscillators for Vulcan CPA. Professor Hutchinson's group at Imperial College for the development of regenerative amplifiers and contrast ratio measurements also for Vulcan CPA. Professor Sibbett's group at St Andrews University for the development of various femtosecond techniques for Sprite sub-picosecond pulses and Professor New's group at Imperial College for the development of theoretical models for the Sprite Raman beams.

2. Vulcan CPA

A measured intensity on target of 10^{19} W cm^{-2} from a single beam with a peak power of 35 TW was achieved on Vulcan at the end of 1994.

Such ultra high intensity on target was made possible by a combination of novel oscillator development (Southampton), advanced diagnostic development and CPA systems studies (Imperial College), and target area and Vulcan laser engineering (RAL)

2.1 Oscillator

Following the demonstration of highly stable, efficient operation of a diode pumped 1.053 μm Nd:YLF oscillator, diode pumping was chosen as the optimum route for the provision of the sub-picosecond pulses required for the CPA Joint Project on Vulcan. The Optoelectronics Research Centre at Southampton University undertook the development of a suitable device, capable of delivering stable sub-picosecond pulses at the nJ level for injection into the Vulcan amplifier chain.

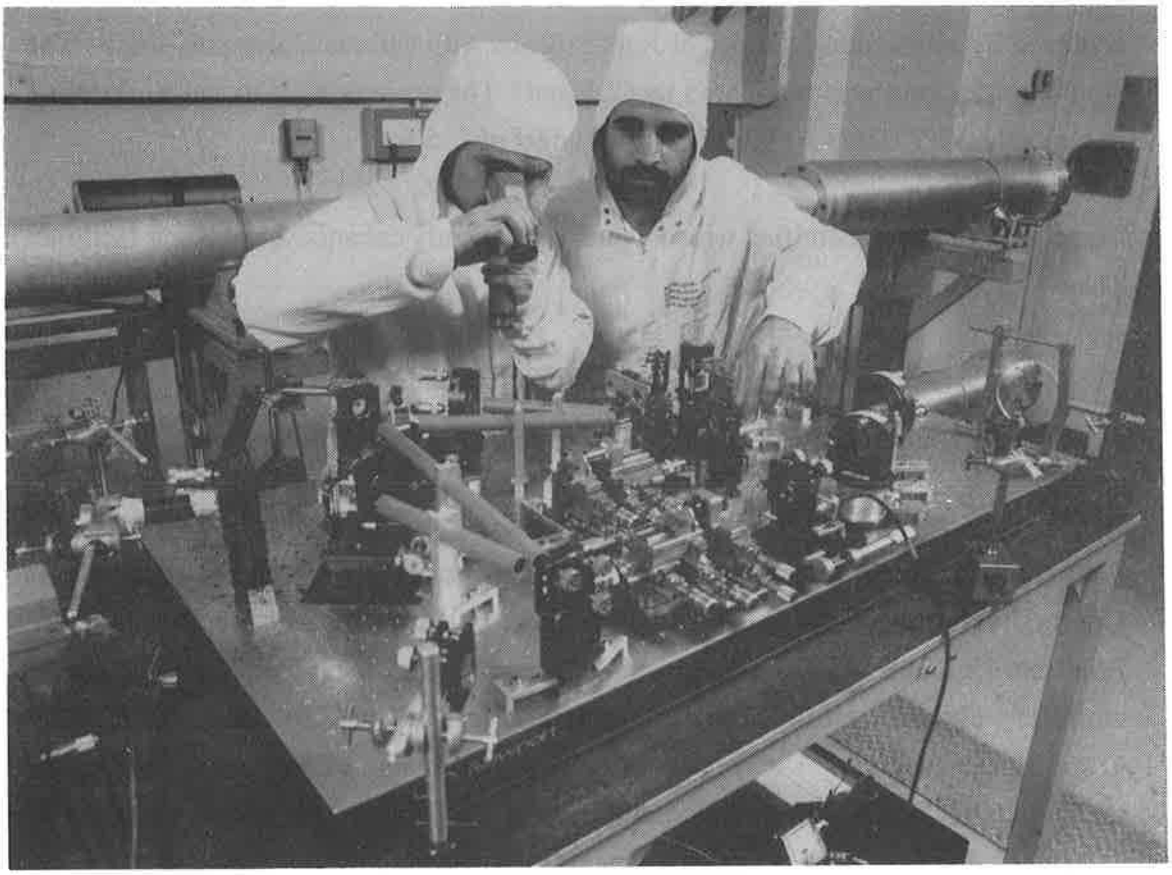


Fig. 1. Nd-LMA Oscillator

Nd-LMA was identified as the most suitable laser medium, which was operated initially using a $TiAl_2O_3$ pump source. Diode pumping and mode locking was achieved towards the end of the first year of the project, and a fully engineered version was delivered to the CLF in August 1993. This oscillator, which is capable of operation at 500fs, was used in the experiments which achieved the 35 TW output, and is now operated routinely as the main Vulcan CPA oscillator.

2.2 Modelling

A detailed understanding of all aspects of pulse propagation in Vulcan in CPA mode was essential for the optimum optical system design. Imperial College undertook modelling of the system, incorporating spectral narrowing and gain saturation in the laser amplifiers, and the transient non-linear effects which affect the propagation of the stretched and compressed pulse in the CPA system.

2.3 Diagnostic development

At an irradiance on target of 10^{19} Wcm^{-2}, pulse-to-background contrast is a crucial physics issue. In this regime, prepulse at the 10^{-6}-10^{-7} level can dominate the physics of the laser/target interaction. Measurement of prepulse at such levels is extremely complex. The Imperial College group designed and commissioned a novel device based on the third order cross correlation of the pulse with its second harmonic. This unique instrument enabled an unambiguous measurement of the contrast at 1.05 μm to be obtained. Best performance to date is at the 3.10^6 level.

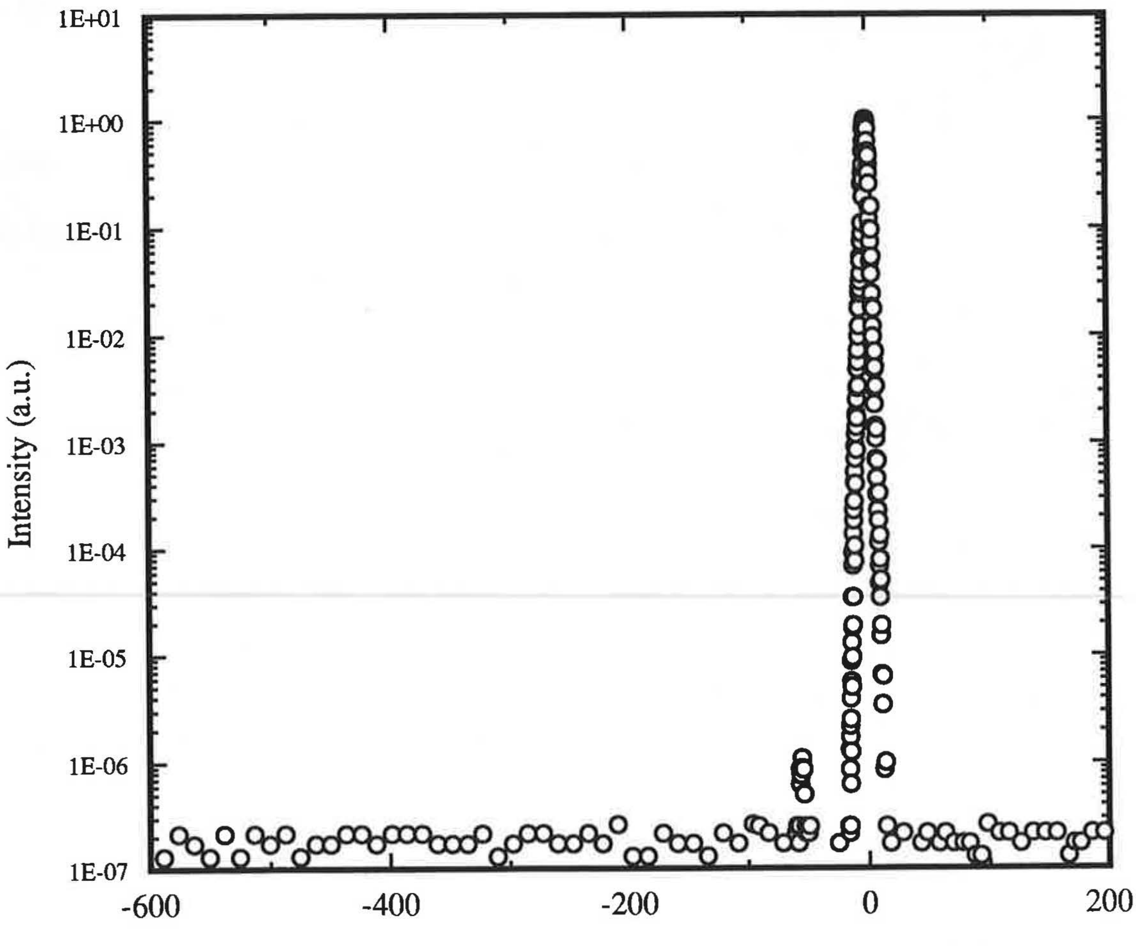


Fig.2 Measurement of Contrast ratio using 3rd Order Correlelator

2.4 Target area enhancements and CPA operations

The joint project funded the installation of the large aperture CPA pulse compressor, vacuum beam transport, and the all reflective beam delivery and focusing system required for ultra-short pulse operation of Vulcan.

Modifications to the pre-amplification stages of Vulcan were made to amplify the nJ oscillator output to the μJ level for injection into the existing amplifier chain. This was accomplished by re-staging 9mm rod amplifiers in a double pass configuration to provide additional gain.

Facility enhancements were brought on-line progressively during the Joint Project to give users access to the improved facilities as soon as they became available.

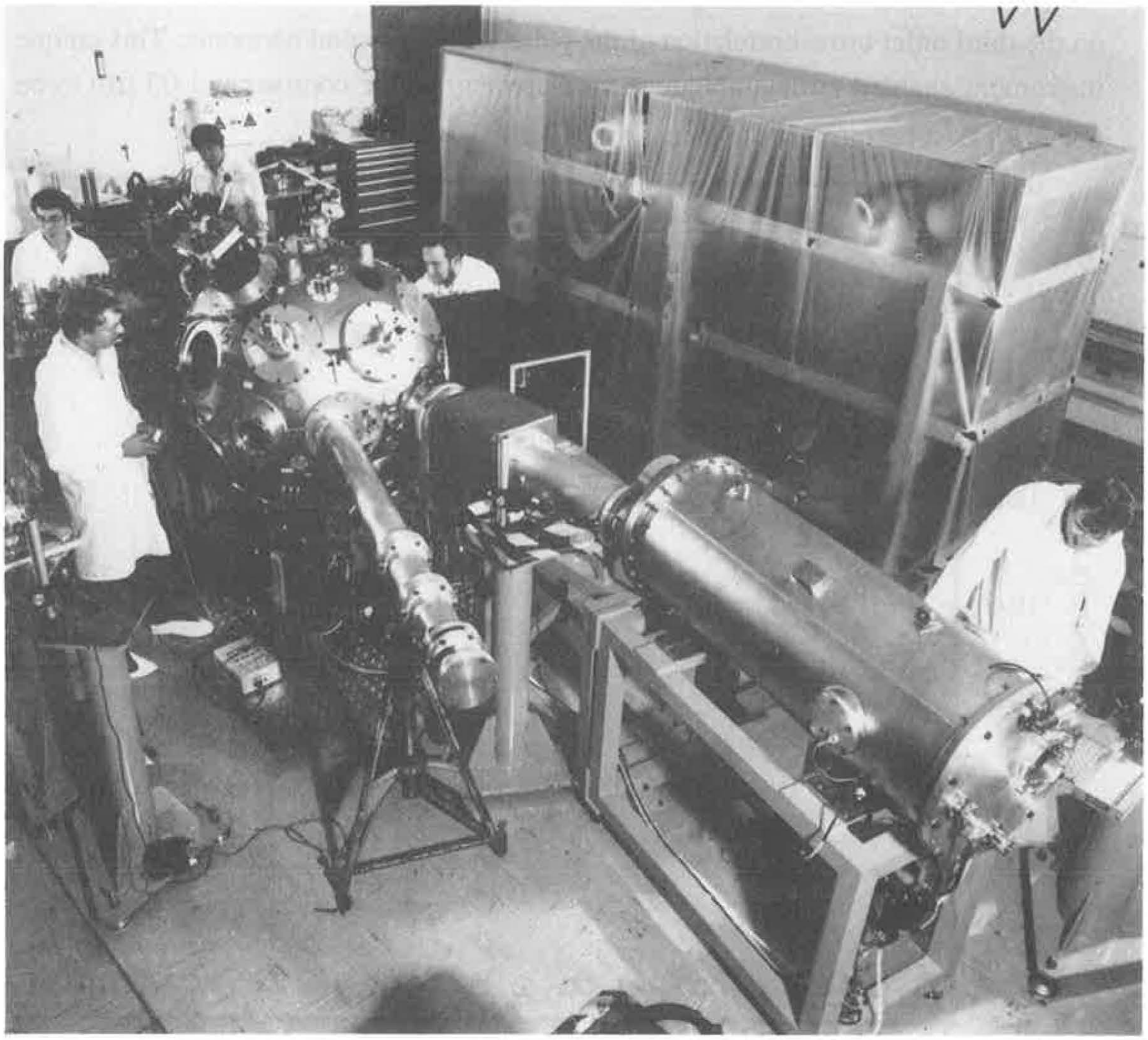


Fig.3. Vulcan TAW showing compression chamber and target chamber

2.5 Regenerative amplifier

A major part of the Imperial College contribution to the project has been the design and construction of a 10Hz YAG-pumped $TiAl_2O_3$ regenerative amplifier. Systems studies at I.C. showed that the short pulse performance of Vulcan is limited to 700fs by spectral narrowing in the amplifiers, and that further reductions in pulse duration are available if less optical gain is provided in Nd:glass. The regenerative amplifier is an essential step towards Vulcan operation in the 300fs regime, designed for an optical gain of 10^5 without significant spectral narrowing.

Measurements made on the system running at I.C. confirm that the design specification of 100 μJ at 1.05 μm has been exceeded by more than an order of magnitude. The amplifier will be moved to RAL in April, where it will be tested in the environment of the laser hall before commissioning on Vulcan.

3. Subpicosecond Pulses on Sprite

The University of St Andrews was involved in all stages of this project which was also linked to work at The Max-Planck Institute, Göttingen. The CPA technique was applied to a UV laser for the first time. A power of 1 TW was delivered to target in a pulse of 290 femtosecs duration. Focused irradiance upto 10^{19} W cm^{-2} at $\lambda = 248$ nm was achieved.

3.1 Front end

A new Ti:sapphire oscillator was purchased (Spectra-Physics Tsunami) which provided stable, transform-limited pulses of 100 fs duration at a wavelength of 746 nm. A selected pulse was amplified to 200 μJ in a specially developed hybrid Dye/Ti:sapphire amplifier. Doubling and mixing in BBO gave 2 μJ at 248 nm with a pulse duration of 150 fs.

An off-axis discharge-pumped KrF amplifier was used to amplify these pulses with a novel double-pass pulse stretcher between the two passes of the amplifier. The resultant output energy was 100 μJ with a pulse duration of 13 ps.

3.2 Amplification and recompression

The pulses were amplified in the two electron-beam-pumped KrF lasers, "Goblin" and "Sprite" to an energy of 1.5 J. Spectral narrowing from 80 cm^{-1} to 60 cm^{-1} has the effect of increasing the pulse duration to 290 fs. The pulses were recompressed on a pair of parallel diffraction gratings with a bare aluminium coating. To avoid damage to the gratings the "on target" laser energy was limited to around 300 mJ.

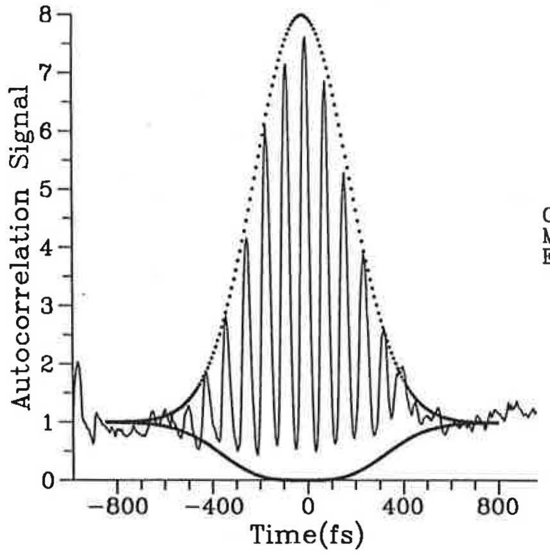


Fig. 4 Autocorrelation trace of the recompressed pulse measured in the Sprite target area.

3.3. Diagnostics

Pulse durations were measured with a single shot interferometric autocorrelator which was developed for this project. The nonlinear process used was two photon fluorescence in barium fluoride.

Equivalent plane far field monitors showed that using an f/4 off-axis parabaloid for focussing a spot size of 10 μm was obtained giving a peak irradiance of 10^{19} W cm^{-2}.

4. Enhanced Raman beams on Sprite

The enhanced Raman beam project required the development of new computer codes for predicting the behaviour of the unique lightguided Raman amplifiers used on the

Sprite system. This work was undertaken at Imperial College. The RAL team made engineering improvements which has provided considerably enhanced performance up to the TW level.

4.1. Computer Modelling

Two codes have been developed at IC which have proven essential in the modelling of the performance of the Raman amplifiers. A 1D code solves the Pump/Stokes coupled equations in the transient case. This code allows the inclusion of noise on the pump or Stokes and treats the growth of second Stokes. The lightguide effects which give rise to group velocity dispersion are treated crudely by allowing the pump and Stokes wave to travel at different speeds.

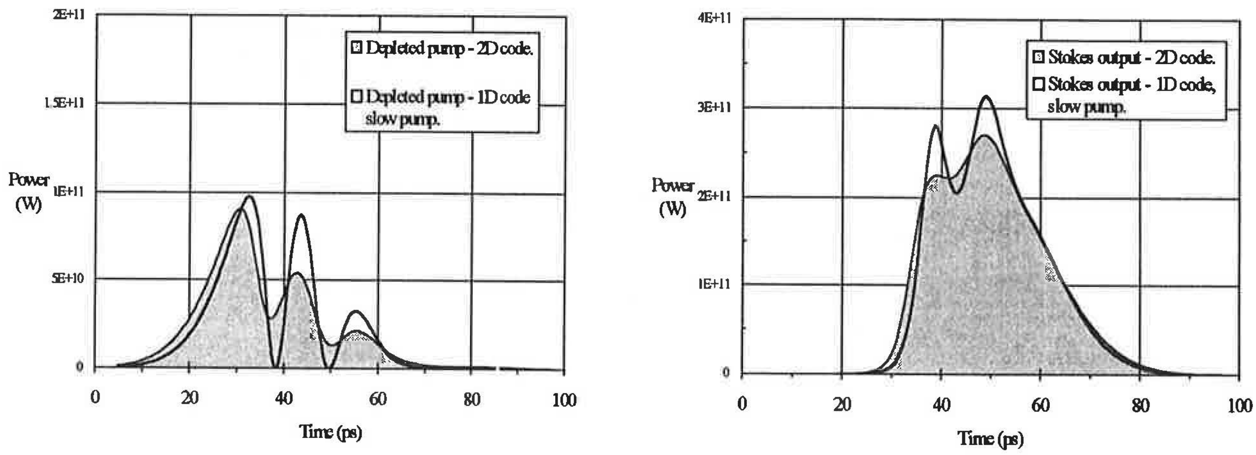


Fig.5. Results of 1D and 2 D models in a lightguided Raman amplifier.

A second 2D code has been developed specifically to investigate the geometric effects brought about by the propagation of "pancake like" optical pulses in the lightguides. This has proven extremely useful in showing that in most cases of practical interest the 1D code describes the process sufficiently well.

4.2 Engineering Improvements

Significant modifications have been made to the Sprite optical multiplexer and Raman amplifier chain. The number of KrF pump beams has been increased from 8 to 12 and their diameter from 8 cm to 10 cm. A new diffraction limited spatial filter has been installed between RA2 and RA3 and the RA3 output beam has been piped to target in argon gas. The result has been a two-fold improvement of the KrF pump energy to RA3 from approx 10 J to 20 J. The Stokes output energy has risen accordingly with typically 13 J being obtained at 25 ps pulse duration. A maximum power of 1 TW was obtained at 10 ps pulse duration. A maximum pump-to-Stokes conversion efficiency of 75% was obtained. The far field divergence of the output beam was 1.4 x diffraction limit which allows focussing to 10^{19} W cm^{-2}.

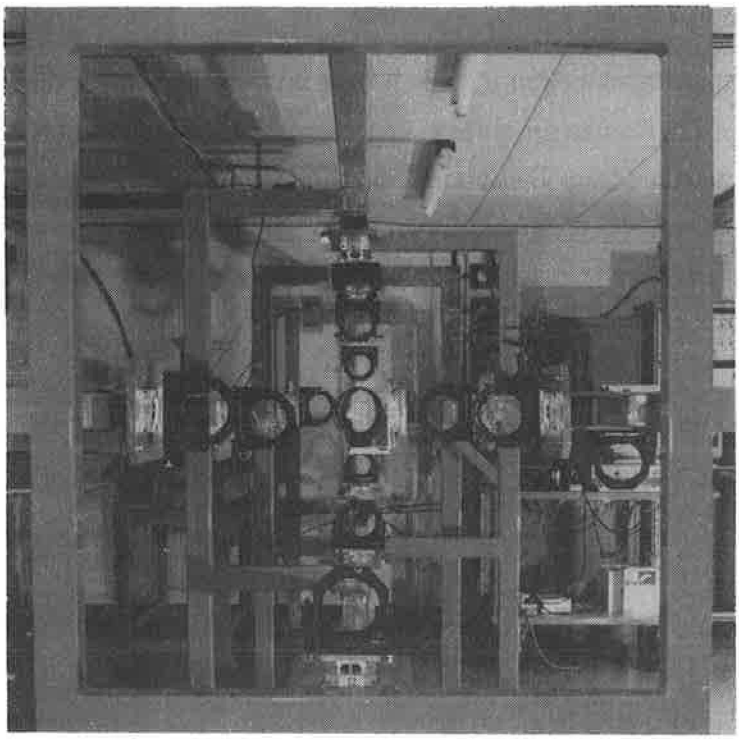


Fig. 6 New array of pump beam mirrors for the final Raman amplifier

5. Scientific exploitation of the improved facilities

These joint projects have provided the CLF with a unique battery of ultra-bright lasers capable of studying interactions of light and matter at irradiances in the 10^{19}W cm^{-2} region over a pulselength span from 300 fs to 10 ps and at two well separated wavelengths (1 μm and 1/4 μm). These new facilities are now being aggressively exploited and publications are emerging (see appendix A).

In recent work sub ps pulses from Vulcan have demonstrated high gain from recombination X-Ray lasers for the first time. In an innovative experiment a team from Bristol university and IC showed that megavolt electron temperatures can be readily obtained at intensities of 10^{18} W cm^{-2} at 1.05 μm. This latter observation has great relevance to the "fast igniter" concept for laser fusion which may offer the possibility of greatly reducing the laser energy required.

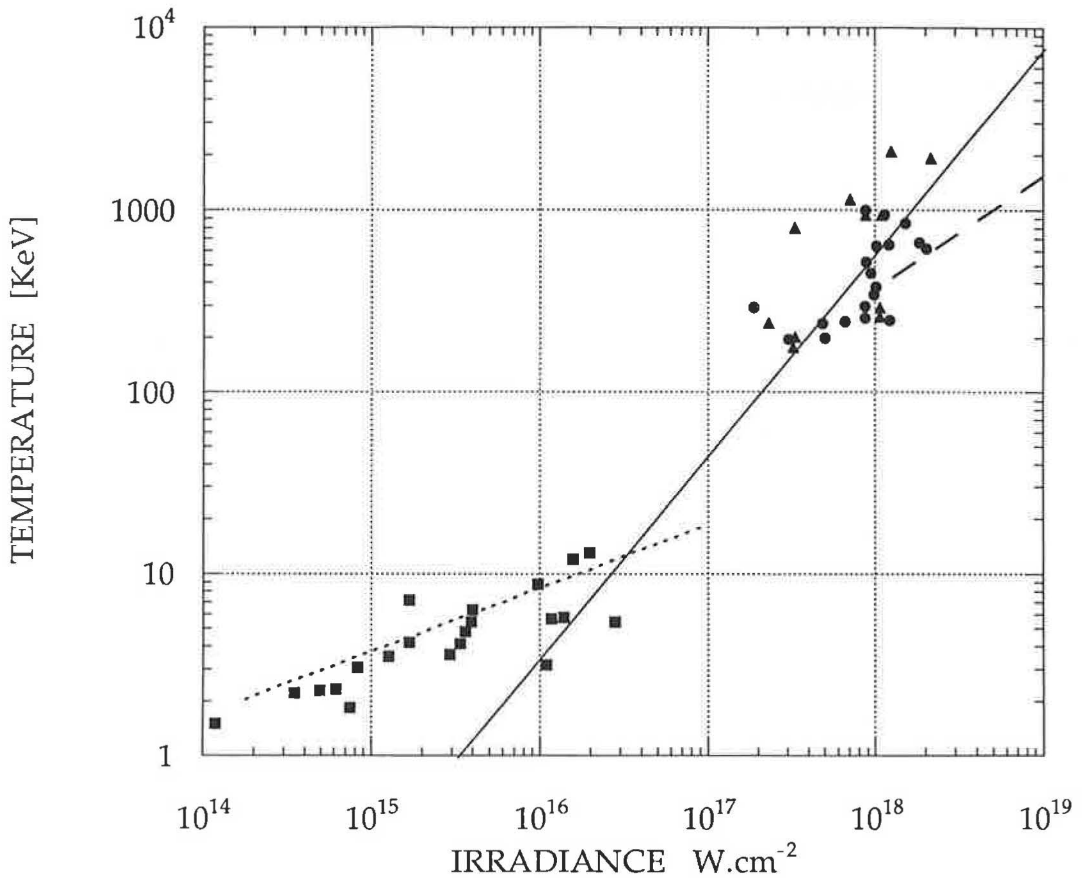


Fig. 7. Variation of electron temperature with irradiance from the Vulcan CPA beam.

The ultra-short pulse capability of the Sprite CPA beam has been exploited in the generation of the 19 th harmonic of 248 nm in the X-UV part of the spectrum from gas jets. Under similar conditions strong plasma heating by SRS has been observed as has the onset of ponderamotive filamentation at ultra-high intensity.

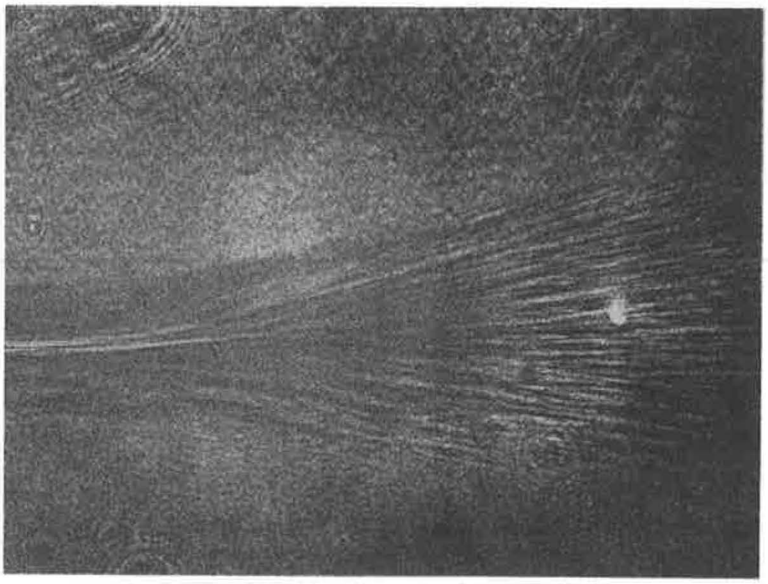


Fig. 8 Ponderamotive filamentation in the Sprite CPA focus at $2x10^{17}$ W cm^{-2} in a neon gas jet.

6. Future options

Vulcan

Options for future development were outlined at a recent meeting with users of the high power lasers at the CLF, with a goal of target irradiances of 10^{20} Wcm^{-2} .

To capitalise fully on the advantages of the regenerative amplifier, a new short pulse oscillator will be required, producing pulses of around 100fs duration. This will enable Vulcan CPA to deliver 350fs pulses to target. This work is currently the subject of a joint grant application between St. Andrews University and RAL.

Higher output is possible with the use of larger compression gratings which are already available, or from improved gratings with higher damage threshold. Grating development will be pursued over the next two years with the aim of producing improved performance for both the Vulcan and Titania CPA facilities.

Titania

The Raman improvements on Sprite are to be used on the forthcoming "Titania" upgrade of the KrF Laser facilities. This is planned to provide for energies on target of a few hundred Joules in a few tens of ps with unique prepulse-free Raman beams.

Titania will be initially configured in the CPA mode and so the improvement of grating damage levels in the UV is of major importance. In addition, the limitation of the bandwidth of KrF by absorption features is not fully understood and is also the subject of ongoing research.

These proposed improvements build on the work already done in the Joint Project period and will continue to keep the CLF in the forefront of high power laser research worldwide.

Appendix A:

REFEREED PUBLICATIONS

M W Phillips, J R M Barr, D W Hughes, D C Hanna, Z Chang, C N Danson and C B Edwards
Self starting additive-pulse modelocking of a Nd:LMA laser
Optics Letters, **17**, 1453, (1992)

M J Shaw, R Bailly-Salins, B Edwards, E C Harvey, G J Hirst, C J Hooker, M H Key, A K Kidd, J M D Lister and I N Ross
Development of high-performance KrF and Raman laser facilities for inertial-confinement fusion and other applications
Laser and Particle Beams **11**, 331 (1993)

C J Hooker, J M D Lister, K Osvay, D T Sheerin, D C Emmony and R L J Cowell
Pulse-length scaling of laser damage at 249 nm in oxide and fluoride multilayer coatings
Optics Letters **18**, 944 (1993)

M J Shaw, G Bialolenker, G J Hirst, C J Hooker, M H Key, A K Kidd, J M D Lister, K E Hill, G H C New and D C Wilson
Ultrahigh-brightness laser beams with low prepulse obtained by stimulated Raman scattering
Optics Letters **18**, 1320 (1993)

M J Shaw, C J Hooker and D C Wilson
Measurement of the non-linear refractive index of air and other gases at 248 nm
Optics Communications **103**, 153 (1993)

S Luan, M H R Hutchinson, R S Smith and F Zhou
High dynamic range 3^{rd} order correlator measurements of picosecond laser pulses
Meas. Sci. Technol., **4**, 1426, (1993)

A R Bell et al
Observations of plasma confinement in picosecond laser-plasma interactions
Phys Rev E,**48**, 2087, (1993)

C N Danson et al
High contrast multi-terawatt pulse generation using Chirped Pulse Amplification on the Vulcan laser facility,
Optics Comm., **103**, 392, (1993)

J R Houliston, I N Ross, M H Key, S Szatmari and P Simon
Chirped Pulse Amplification in KrF Lasers
Optics Communications, **104**, 350-356 (1994)

I P Mercer, Z Chang, C N Danson, C B Edwards, M H R Hutchinson and R G Miller
Diode pumped picosecond Nd:YLF laser oscillator at 1053nm
Optics Comm., **107**, 77, (1994)

I N Ross, C J Hooker and J R Houliston
A Simple Technique to assist in Temporal Profile Diagnostics of Short Pulses
Optics Communications, **107**, 111-114 (1994)

J R Houliston, M H Key and I N Ross
Modelling of Saturated Chirped Pulse Amplification and Compression
Optics Communications (in press)

J Zhang and M H Key
Hydrogen-like recombination X-Ray lasers using psec pulse drivers
Appl Phys B, **38,** (1994)

K Osvay, I N Ross, C J Hooker and J M D Lister
Laser-excited non-linear properties of barium fluoride and its application in a single-shot spatially insensitive autocorrelator
Accepted for publication in Applied Physics B

I N Ross, A R Damerell, E J Divall, J Evans, G J Hirst, C J Hooker, J R Houliston, M H Key, J M D Lister, K Osvay and M J Shaw
A 1TW KrF Laser using Chirped Pulse Amplification
Optics Communications (in press)

J Zhang, M H Key, S J Rose and G J Tallents
Calculations of high-gain recombination X-ray laser at 4.55 nm
Phys Rev A,**49,** (in press)

A A Offenberger, W Blyth, A E Dangor, A Djaoui, M H Key, A Mori, Z Najmudin, S G Preston and J S Wark
Optical Ionization and heating of gases by intense picosecond KrF laser radiation
Lasers and Particle Beams (in press)

A A Majdabadi, D W Hughes and J R M Barr
A subpicosecond laser diode pumped LMA laser
Optics Letters (submitted)

C N Danson et al
>10^{19} Wcm^{-2} Operation of the VULCAN high power Nd:glass laser facility
Optics Communications (submitted)

PUBLISHED CONFERENCE PROCEEDINGS

G J Hirst, R Bailly-Salins, C J Hooker, M H Key, A K Kidd, J M D Lister, I N Ross and M J Shaw
The high-brightness KrF/Raman facility at RAL: Recent results and scheduled developments
Proc. International Conference on Lasers '92, pp131-138

M H Key et al
Generation of Ultra-bright beams in high energy Nd:glass and KrF laser systems
Second Topical Meeting on Physics with Intense Laser Pulses, OSA Proceedings on Short wavelength V, PB Corkum, MD Perry (eds) **17**, 21, 1993

C N Danson et al
Chirped Pulse Amplification experiments on the Vulcan Nd:glass laser facility
Short Pulse High Intensity Lasers & Applications II, SPIE **1860**, 10, 1993

I N Ross, G Bialolenker, J Evans, K Hill, G J Hirst, C J Hooker, J R Houliston, M H Key, J M D Lister, G New, W Sibbett, S Szatmari and D C Wilson
Development of high brightness KrF lasers using Raman and ultrashort pulse CPA techniques
Short Pulse High Intensity Lasers & Applications II, SPIE **1860**, 21, 1993

Appendix B

Finance

The total budget for the Joint Projects was £750k, of which £380k was allocated to the Vulcan CPA enhancement, £197k to Sprite CPA, and £173k to the Sprite Raman upgrade.

Contracts were placed with the participating universities to a total value of £284k as follows:

Imperial College (Vulcan CPA)	£155k
ORC Southampton	£58k
St Andrews	£23k
Imperial College (Sprite Raman)	£22k

The university contracts supported a total of 7 years RA effort.

Appendix C

Membership of The Joint Project Management Committee (RAL unless stated)

Prof M H Key	(Chairman)
Mr N Allen	(Secretary)
Dr J R M Barr	(Southampton)
Dr C B Edwards	
Prof D C Hanna	(Southampton)
Prof M H R Hutchinson	(Imperial College)
Prof G H C New	(Imperial College)
Dr I N Ross	
Dr M J Shaw	
Prof W Sibbett	(St Andrews)
Mr W T Toner	
Mr B E Wyborn	