P 406 419

Generation of Ultrabright Beams in High Energy Nd:Glass and KrF Laser Systems

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Introduction

The development of ultrabright lasers is progressing rapidly particularly in the direction of table-top-terawatt systems operating at high pulse repetition rate with relatively low pulse energy. The highest pulse energies and highest absolute powers are being generated by the adaptation of larger-scale high energy laser systems operating in single pulse mode. The maximum focused intensity from either type of laser is determined by the beam brightness B which can be expressed in units of Watts cm^{-2} $sterad^{-1}$. The focused intensity is then approximately B/f^2 where f is the focal length to diameter ratio of the focusing optic. Brightness can be expressed as $B = PS/\lambda^2$ where P is the power, λ the wavelength and S the Strehl ratio, quantifying the ratio of brightness in a beam with less than diffraction limited quality to that in a diffraction limited beam.

With higher power in larger laser systems, higher brightness is possible in principle providing that good wavefront quality can obtained over larger apertures, though currently the table-top laser systems produce comparable brightness to larger aperture lasers of similar wavelength. Short wavelength can increase brightness through reduction of diffraction limited divergence.

Laser systems operating in the ultraviolet therefore offer prospects for the highest brightness and focused intensity while, for similar wavelength and brightness, more powerful lasers offer more area irradiated at a given intensity. Increasing the irradiated area is important for applications. For example, longer confocal parameter increases harmonic conversion efficiency or accelerated particle energy in plasmas. Similarly longer length in line focus irradiation increases the gain-length product in transversely excited X-ray lasers or longer confocal parameter could similarly increase the gain-length in multi-photon-ionisation X-ray lasers with axial pumping. It seems likely that larger laser systems operating with short pulses and high brightness and short wavelength will be first to produce X-ray laser action on the new ultrashort pulse schemes just as the realisation of collisionally excited XUV lasers was first accomplished with the largest available laser facility.

OSA Proceedings on Shortwavelength V, 1993, Vol. 17
Paul B. Corkum and Michael D. Perry (eds.)

In this paper, development of ultrabright modes of operation of a large Krypton Fluoride laser facility, Sprite, and a large scale Neodymium-glass laser facility, Vulcan, is reviewed. These lasers are operated as user facilities for visiting teams from UK Universities and their overseas collaborators. Their development is being carried out jointly with UK University groups from Imperial College, London, University of Southampton and St Andrews University and bilateral collaboration in the development of ultrashort pulse KrF lasers with the Göttingen Max Planck Institut also contributes to this work.

Krypton Fluoride Pumped Raman Laser Development

Krypton fluoride lasers have a low saturation fluence (2 mJ cm^{-2}) and a short excited state lifetime (2 ns). Large aperture electron beam pumped amplifiers are available with duration of excitation of the order of 100 ns. They can readily be saturated with energy extraction approaching steady state efficiency by trains of pulse separated by the upper state lifetime.

Delivery of their energy in a single pulse can be accomplished with angular multiplexing of the output beam and the use of the angularly separated beams to pump beam combining Raman amplifiers. This principle has been implemented with the Sprite KrF laser facility at the Rutherford Appleton Laboratory (1). An attractive feature of the Raman amplifier scheme is its efficient conversion of multiple beams of imperfect beam quality into a single beam of near diffraction limited beam quality. A brightness of 1.5 x 10^{20} W cm^{-2} sterad^{-1} has been obtained with the Sprite facility operating at 0.5 TW power in 10 psec pulses. Figure 1 illustrates the system.

A titanium sapphire oscillator operating at 746 nm provides pulses of 10 ps duration. Amplification to the level of hundreds of μJ is obtained in pulsed dye amplifiers operating at 8 Hz. After frequency tripling and spatial filtering, tens of μJ per pulse are produced at 248 nm and amplified to mJ level also at 8 Hz in a KrF discharge amplifier.

Pulses at the first Stokes wavelength (268 nm) are generated by focusing the beam in 1 bar CH_4 and are preamplified in a Raman amplifier with a co-propagating 248 nm pump pulse. After passing through a delay line and a diffraction-limited vacuum spatial filter , about 50 μJ of Stokes pulse energy is available as the input to the final two amplifiers, where the KrF pump beams (originating from multiplexing the 27 cm SPRITE amplifier) are confined within square section light guides (8 x 8 cm in the final amplifier).

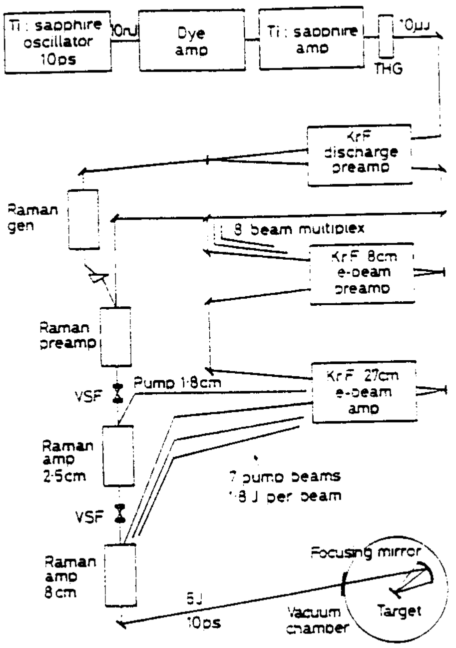
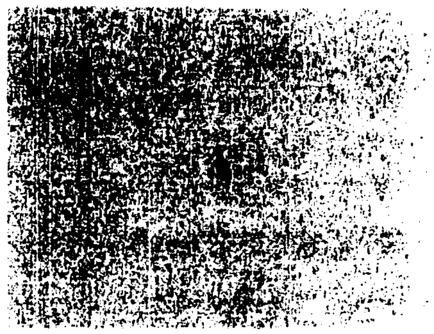


Figure 1 KrF laser pumped Raman laser

The far-field patterns of the pump and Stokes output beams recorded by a UV sensitive CCD camera placed at the focus of a telephoto lens are shown in figure 2. There is a major enhancement of beam quality in the Stokes beam relative to the pump beams. The Stokes far field is characterised by a FWHM of 1.7 x the diffraction limit. The peak brightness for the shot shown in Figure 2 is 1.5 x 10^{20} W cm^{-2} sterad^{-1}. The beam Strehl ratio is 0.22. The 8 cm Raman beam is focused onto target at f/3.8 by an off-axis paraboloid, so the potential maximum intensity on target is 8 x 10^{18} W cm^{-2}.

Pump beam far-field
20 x diffraction limit



Raman beam far-field
1.4 x diffraction limit

Figure 2 Laser pump and Raman beam far fields

For a laser based on stimulated Raman scattering in the transient regime (pulse length 10 ps << dephasing time 32 ps) a prepulse is not expected theoretically since the optical phonon wave has to grow in the laser medium before the pump can be converted into Stokes light. A consequence important for some applications is that the rise time of the Stokes pulse can be considerably faster than that of the pump and the prepulse greatly suppressed. Figure 3 shows simulations of this effect using a 1D code for the case of a generator where the Stokes pulse grows from noise. As the steady-state Raman gain parameter $\gamma I_p L$ (where γ is the Raman gain coefficient, I_p the peak pump intensity and L the interaction length) is increased, the rise time of the Stokes pulse decreases. Prepulse suppression is by a factor of 10^{11} below that of the Gaussian pump. Further amplification in transient Raman amplifiers does not degrade the pulse rise time or the suppression of prepulse.

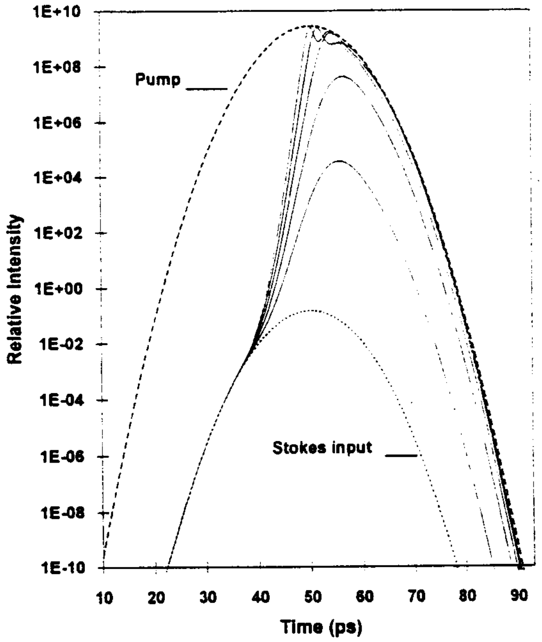


Figure 3 Modelling of Stokes pulse generation in Raman medium

The Raman amplifier system is well suited to operation at pulse length from about 100 psec to 10 psec with the pulse energy being approximately constant. (Operation with shorter pulse length becomes difficult due to spectral broadening of the Raman pump beams by self phase modulation which degrades the gain of Raman amplifiers). The system is scalable and suitable also for multibeam operation when angularly multiplexed Stokes beams are propagated through the Raman amplifiers. We are currently constucting a larger Raman laser system at the Rutherford Appleton Laboratory using a 40 cm diameter output amplifier which will be capable of delivering 20 TW peak power in 10 psec pulses from 4 beams.

KrF Laser Chirped Pulse Amplification and Compression CPAC

The KrF medium is capable of amplifying pulses of duration < 100 femtoseconds but nonlinear effects prevent the extraction of the saturated energy from large aperture KrF amplifiers in the limit of such short pulse duration. CPAC operation(2,3) restores in principle the possibility of delivering the full pulse energy in a < 100 fs pulse. Application of this principle to the Sprite facility as illusrated in figure 4 gives the possibility of 10 TW, 100 fs pulses.

The CPAC system for Sprite is based on a matched grating stretcher - grating compressor combination using 3600 lines per mm gratings in first order Littrow at an angle of incidence of 26°. A 100 fs, 760 nm pulse from a titanium sapphire generator is preamplified by YAG pumped dye and titanium sapphire amplifiers, frequency tripled and then stretched to 10 ps. Amplification in a discharge excited KrF amplifier and in two e-beam pumped amplifiers raises the energy to 1.8 J. Recompression on gratings separated by 1.5 m is accomplished by adjusting the spacing in the stretcher. Figure 4 presents also a a table of relevant beam parameters from oscillator to target. The extra stretch due to group velocity dispersion (GVD) is shown and totals about 1 ps. Also shown are the increments of nonlinear phase change or B-integral. The principal result of this B-integral is to change the pulse chirp through self phase modulation (SPM). Both GVD and SPM effects can be compensated by a small mismatch between stretcher and compressor.

A significant difference between KrF and solid state lasers when using CPAC is the different level of gain saturation. The chirped pulse profile is distorted by gain saturation and therefore the spectrum is similarly distorted. We have modelled the effect on the recompressed pulse for an initially transform limited Gaussian pulse and a medium with a Gaussian variation of gain with frequency.

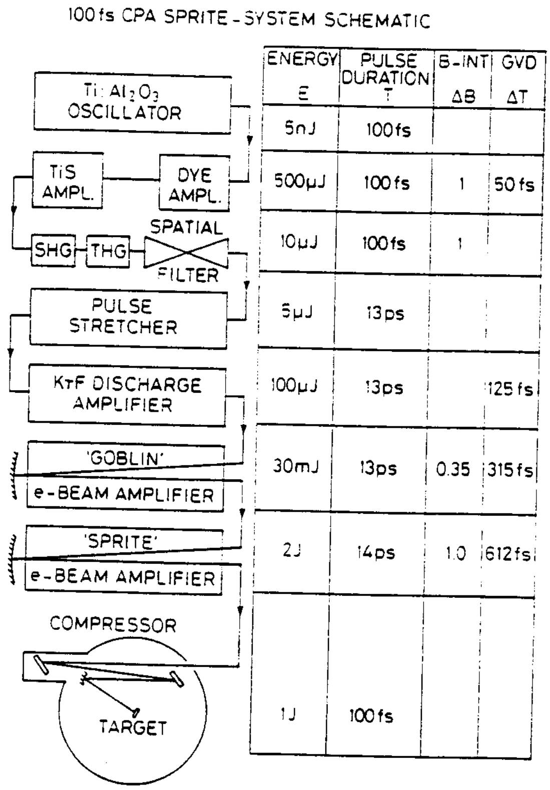


Figure 4 Ultrashort pulse CPAC operation of Sprite laser

Rate equations were used to describe gain saturation and a compressor which exactly cancels the linear chirp of the stretcher was assumed. For zero gain saturation the input short pulse is reproduced exactly on compression. At 3x the saturation fluence, which is typically that achieved in Sprite, the compressed pulse duration is reduced by a few percent but the wings of the pulse at low intensity are broadened, for example by a factor of 1.3x at 10^{-8} of peak intensity. This broadening does not give a significant intensity pedestal and appears to be an acceptable characteristic of CPAC in the KrF laser. The most exciting prospect offered by CPAC operation of Sprite is its potentially record brightness. The Sprite CPAC system is now being tested and its beam quality in direct amplification of a single KrF beam has been improved to a Strehl ratio at low intensity of 0.3. If this beam quality is achieved at 10 TW in the compressed pulse the brightness could reach 3 x 10^{21} W cm^{-2} $sterad^{-1}$ and the focused intensity could reach 10^{20} W cm^{-2} exceeding that of any other laser system.

Neodymium Glass Laser CPAC

The multi-beam Vulcan glass laser facility has already been adapted(4) for chirped pulse operation on one of its 150 mm beam lines which can deliver energies of several hundred Joule in nanosecond pulses. A generator and preamplifier system has been installed using a diode pumped additive-phase-mode-locked oscillator to produce transform-limited 2 psec pulses. Pulse stretching by gratings and preamplification in small aperture glass laser rods feeds an 80 ps stretched pulse to the main chain at the millijoule level (as a parallel option with other pulse generators). A target irradiation facility at the output uses 30 x 15 cm gratings with 1900 lines/mm in Littrow configuration to produce the compressed pulse in vacuum. An f/3 off-axis paraboloid focuses the beam. Extensive characterisation of the system has demonstrated 8 TW output in 2.4 psec pulse as shown in figure 5.

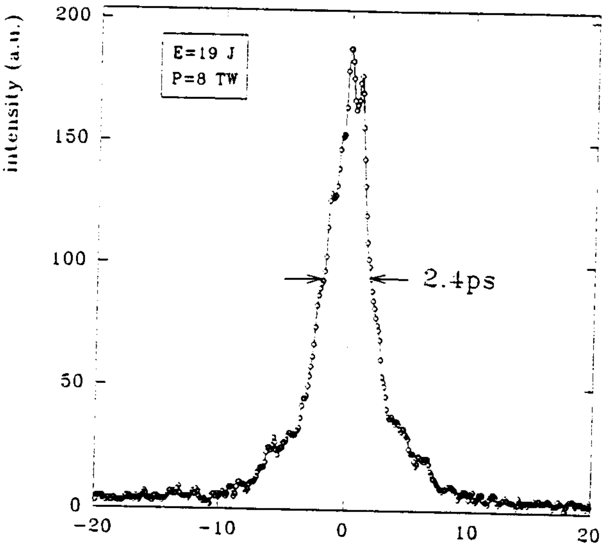


Fig 5 Autocorrelation trace of CPAC pulse.

The far field quality of the beam has been measured to be about 5 times diffraction limited, focusing to full width half maximum of 15 μm by 50 μm in the directions perpendicular and parallel to the dispersion direction. The larger extent in the dispersion direction is attributed to imperfect parallelism of gratings and should be reducible to 15 µm also. The brightness at present is 2×10^{19} W cm^{-2} sterad^{-1} and the focussed intensity is 10^{18} Wcm^{-2}. B integral effects have been seen to broaden the pulse at higher energies. This pulse broadening could be tuned out by readjustment of the grating separation. Pulse contrast ratio has been measured with a 2-channel third order correlator(3) and shown to be better than 10^6:1. A diode pumped LMA generator producing 700 fsec pulses has also been developed and will shortly be installed on this system. Upgrading to 50 TW operation with the new generator and with increased pulse energy is planned during the next year.

Applications

The KrF laser pumped Raman laser facility has been operated as a user facility for visiting teams for two years, while the glass laser CPAC facility has been similarly made available since the beginning of 1993. The KrF CPAC facility is scheduled for operation on behalf of user teams from June 1993. A wide range of scientific study is in progress or planned for these lasers. Work already carried out with the Raman facility includes observations of production of ultradense plasmas from solid targets(5) and studies of multiphoton ionisation and heating of gaseous targets(6). With the CPAC glass laser fast proton energy spectra from solid targets have suggested that fast particle energies scale with $I\lambda^2$ similarly to irradiation with longer pulses(7) and stimulated scatter in the strong interaction regime has been studied in gaseous targets. Initial experiments with the KrF CPAC beam will measure residual temperature in multiphoton ionised gaseous target and generation of high harmonics in ionic media will be investigated. X-ray laser related experiments using both KrF and glass laser CPAC beams are also planned in the near term.

Acknowledgements

This work was supported by the Science and Engineering Research Council and by the Max Planck Foundation.

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