Non-solid, non-rigid optics for high power laser systems.

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ABSTRACT

Non-solid and non-rigid optics employ gas and liquid transmission and reflection, as well as flexible membranes to influence laser beams, laser driven particle beams and harmonic generators. Some examples are acoustic gratings, phase conjugate mirrors, Raman cells, gas-jets, gas and flame lenses, gas capillaries, plasma cones, mercury mirrors and rotating and aerodynamic windows. Industrial scale laser propulsion, laser fusion, laser accelerators, lithography and laser isotope separation will necessitate handling average beam powers very different from present day single shot demonstrations. Standard solid state optics may prove incapable of handling such conditions.

Keywords: Non-solid optics. Gas lenses. Flame lenses.

1. INTRODUCTION

Whereas before the appearance of the first lasers in 1960 almost all optical apparatus involved solid glass, crystals or fixed metal surfaces (with rare exceptions such as optical activity in liquids and gas discharge spectroscopy), very shortly thereafter, a whole range of experiments were performed with non-solid media. And with the advent of high power laser systems, flexible or moving solid devices became or are becoming useful. In this article we will briefly review non-solid or non-rigid optical devices (NSNRO) developed in different countries. We then describe similar devices developed or improved in laboratories in South Africa or the UK. And finally we describe or propose various applications of NSNRO.

2. SOME NON-SOLID, NON-RIGID OPTICAL DEVICES.

2.1. Non-solid devices.

To cover in detail all NSNRO devices would require several tomes. Here we simply intend to list a few important devices, some frequently used, some almost forgotten. The study of parametric processes and non linear waves gave birth soon after the invention of the laser, to the phase conjugate mirror (1), the four wave mixing amplifier and the Raman cell: fig. 1 a,b,c. (2). Before the development of fiber optics and before the realization that power conversion into laser light and back was very inefficient, high hopes were raised for information and power transmission by gas lenses and laser beams.

Various gas lenses were developed at Bell Labs by Marcuse (3), Gloge *et al.* (4) and also in Russia and Poland by Martynenko (5) and Sinkiewicz (6) . These were the compressed air negative lens, the drawn air gas lens, the spinning pipe gas lens (SPGL) and the gas dynamic lens: fig 1 d,e,f,g. At Natal, we invented the Colliding Shock Lens (CSL). Other older, laser transmission, focusing and isolation devices are the laser produced plasma isolator and plasma lens (7) and the laser spark generated plasma isolator and spatial filter invented at Aldermaston by C.L.M. Ireland (8) and employed in self-triggering mode on the Nova laser: fig. 1 h,i. Recently three important breakthroughs have been achieved with multi-terawatt or petawatt lasers. Gas jet illumination produced 80 MeV pulses of mono-energetic electrons (9). At somewhat lower powers, the same experiment with focal intensities in

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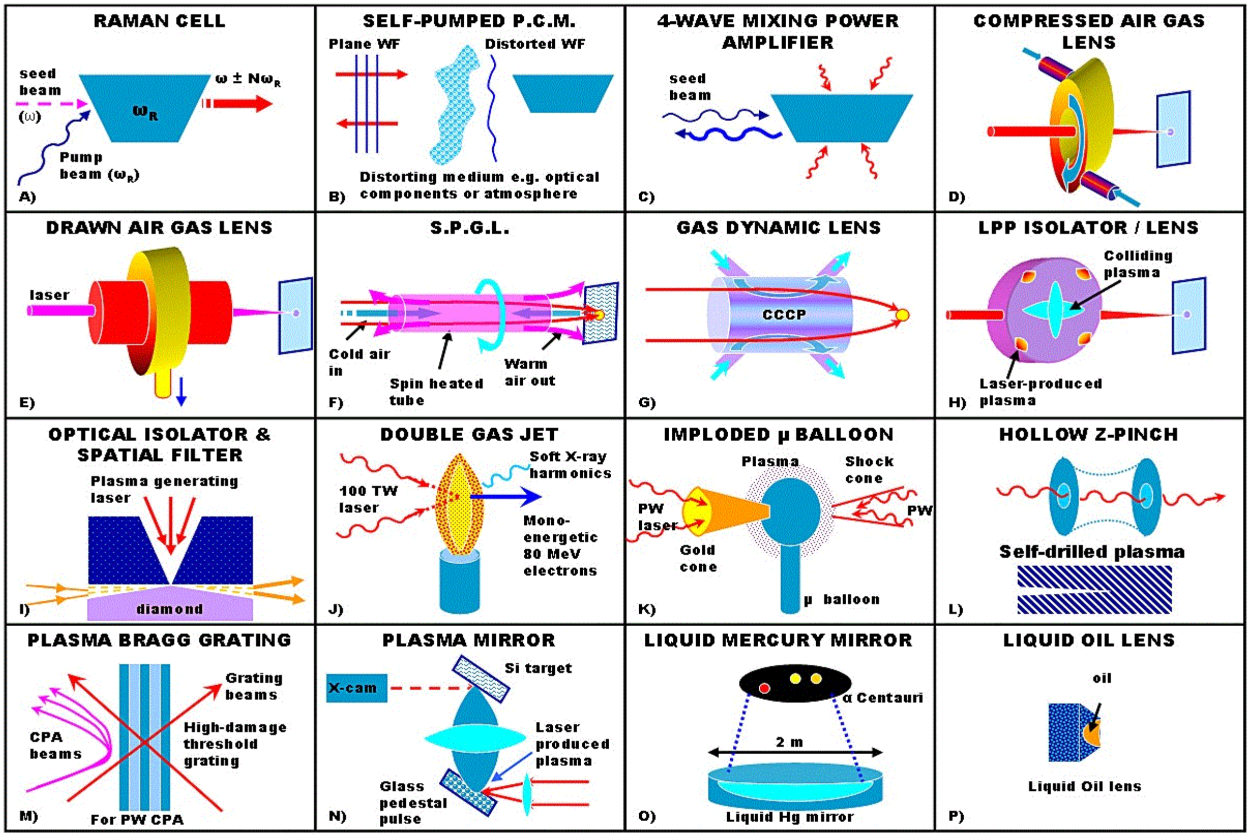


Figure 1. a. Raman cell converts pump power into other wavelengths. b. Self-pumped Phase Conjugate Mirror (PCM) corrects distortions introduced by e.g. laser amplifiers or the atmosphere. c. Four wave mixing amplification. d. Vortex of compressed air, negative lens. e. Drawn air gas lens. f. Spinning pipe gas lens (SPGL). g. Russian large aperture, gas dynamic lens. h. Laser produced plasma (LPP) isolator and plasma lens. i. Aldermaston spatial filter and LPP isolator. j. Irradiation of gas jets by petawatt laser pulses produces monoenergetic e-beams or soft X-rays. k. Conventionally imploded μ-balloon is "fast-ignited" with gold cone focused PW laser. (In the future a shock-driven plasma-cone could be envisaged). l. Lopes hollow pinch or self-drilled plasma waveguides for TW/PW lasers. m. Plasma Bragg Gating (PBG) for Chirped Pumped Amplifier (CPA) in PW systems. n. Plasma mirror removes pedestal portion of TW/PW pulse. o. Electronic liquid lenses for small aperture and ultra large aperture liquid mercury mirrors.

the 10^{13} W.cm^{-2} range yields high harmonics in the EUV spectral range. (10, 11). And a gold cone focused a GEKKO PW beam into a pre-compressed fusion target, demonstrating Tabak's concept of Fast Fusion Ignition: fig. 1 j,k (12). Such gold cone ignition is inconceivable for a rep-rated power station. However, our colliding shock techniques described in section 3.3 might easily be adapted to generate PW focusing cones at repetition rates of a few Hz.

In the context of laser accelerators, we think that attempts to generate plasma wave-guides will extend laser acceleration into the GeV range. One such wave-guide is the Lopes (13) or Hosokai (14) Z-pinch plasma channel generated between two disc electrodes: fig. 1 l. Two novel plasma devices are the plasma Bragg grating (15) and the plasma mirror (16): fig. 1 m,n. The former could serve to replace the extremely delicate and expensive gratings used for chirped pump amplification (CPA) central to PW lasers. The latter serves to remove the long pre-pulse or pedestal from ultra high power pulses, but might find many other applications, for instance in fusion and laser propulsion. Finally we mention two "liquid optics" devices. The liquid lens and the mercury mirror: fig. 1 o,p. Both these devices are becoming quite common in everyday optics and in amateur astronomy. Large aperture mercury mirrors have only a small near-vertical field of view, but all-night automated data collection and multi-latitude operation can overcome this obvious difficulty. It isn't hard to imagine the use of either of these two liquid optics varifocal devices with very high power lasers.

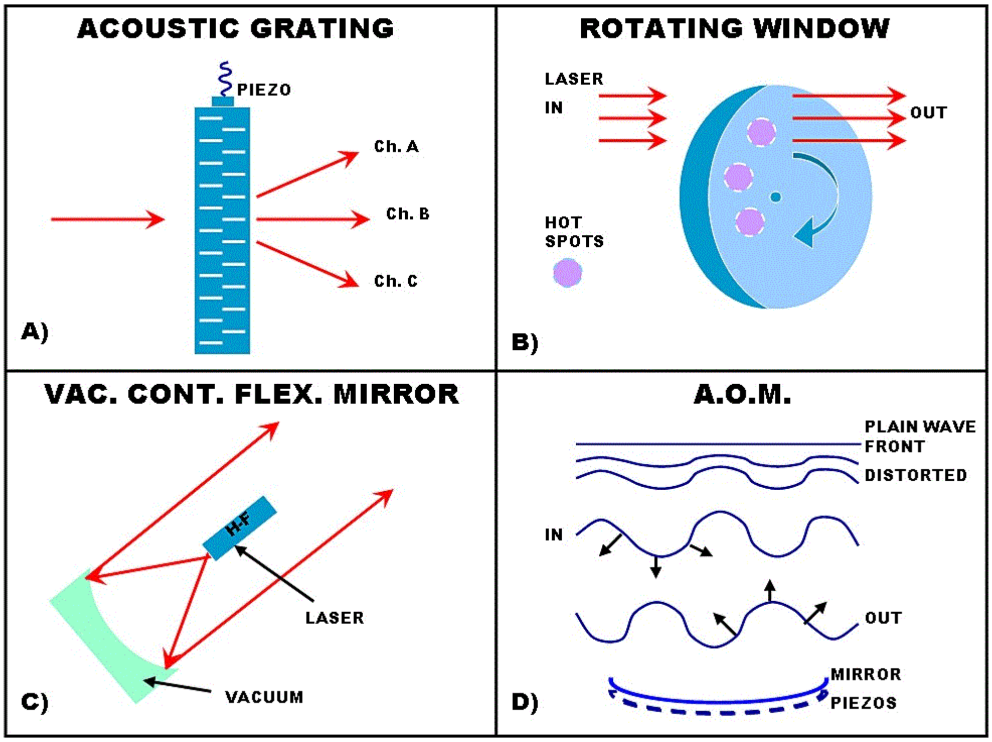


Figure 2. a. Acoustic grating. b. Rotating window for high average power transmission. c. Vacuum controlled adaptive varifocal mirror focuses H-F or D-F laser on remote target. d. Piezo-controlled adaptive optics mirror compensates wave-front distortions in similar fashion to PCM.

2.2. Non-rigid devices

Here again we content ourselves with listing the devices in fig. 2, with a few words for each. The acoustic grating was the first "non-rigid" device used to split laser beams into separate channels: fig. 2a. Rotating mirrors and windows are able to surmount the problems of thermal-lensing/mirror-deformation at high average beam irradiance: fig. 2b. Flexible vacuum controlled mirrors are used by the military to adjust their focal length for irradiation with kJ H-F or D-F pulsed lasers: fig. 2c. Most important of all are "adaptive optics" (AO) mirrors developed for "Star Wars" and later declassified for use in astronomy. They have recently been used to control the focusing of KrF lasers in a target area: fig. 2d(17). It is likely that "AO" will become a crucial feature of laser propulsion of satellites: there is very little difference in focusing an energetic laser beam onto a military target in space and doing the same for a laser propelled satellite.

3. NSNRO IN SOUTH AFRICA

We now describe NSNRO experiments carried out at the University of KwaZulu Natal in South Africa, some in collaboration with the National Laser Center (NLC) and RAL (UK).

3.1. The Spinning Pipe Gas Lens. (M. Notcutt, A. Prause)

The Spinning Pipe Gas Lens (SPGL) was invented by Martynenko in 1985 at the Lyukov Institute of Heat and Mass Transfer in Minsk, USSR. M. Notcutt (18) and one of us "re-invented" this lens three years later with no prior knowledge, due to difficulty in accessing Soviet literature. The SPGL is a thermal lens that overcomes the gravity induced limitations of the aspired lens by spinning the heated pipe. Each half of the SPGL is found to contain three regions, which can be rendered visible with a spinning glass tube and smoke (19): fig. 3a. Region I is cold air sucked along the axis. Region II is a stagnation volume of warm, slightly turbulent air. Region III is a warm sheath of counter-flowing air that gets centrifuged out of the ends. The corresponding temperatures are plotted in fig. 3b. We employed a SPGL to demonstrate the quality of gas lenses by imaging a water tower at a distance of 5 km, sunspots and various phases of the Moon: fig. 4 (20). The SPGL was one meter long, had an internal diameter of 25 mm, was apertured down to about 8 mm and heated to a temperature of about 70^oC.

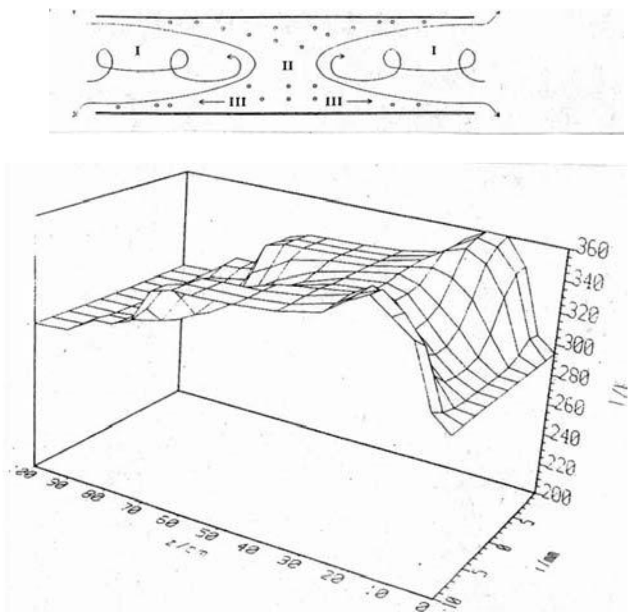


Figure 3. The spinning pipe gas lens. a.The three separate regions of gas flow. b.Temperature profile measured inside a self feeding S.P.G.L.

3.2. The Colliding Shock Lens. (CSL). (R. Buccellato, N. Lisi, M. M.)

The CSL (fig. 5a), invented by R. Buccellato, N. Lisi and one of us (MM) (21) is a versatile pulsed gas lens that as its name implies, results from the collision between a number of shock waves generated by discharges in air. As described in previous HPLA proceedings (II and III), After a series of circularizing Mach additions (fig. 5b), a cigar of dense air is generated, which is the actual gas lens. The lens is varifocal in time. For a small lens, it takes some 3 μs for the aperture to grow from 1 mm to 3 mm, whilst the focal length goes from 20 to 50 cm. A. Conti, recently demonstrated a 1.2 cm aperture CSL, finally proving that the CSL does scale to centimetric and possibly decimetric dimensions. Unfortunately this came at the cost of a CSL energy input of some two hundred Joules and the focal length was around 5 metres. Though too long for most applications, this might be interesting for laser propulsion where the variable focal lengths need to range from a few metres to several kilometers.

3.3. The Virtual Capillary. (A. Conti)

If, rather than generating shocks between opposing electrodes as in the CSL, the shocks are generated by exploding a set of parallel wires, disposed around a cylinder (fig. 6a), a virtual capillary (VC) can be formed in air. The wires are connected in series to ensure shock-simultaneity. The VC experiment produces firstly a strong cylindrical lens, which as in CSL experiments, weakens with a time scale of several microseconds, before becoming hollow (22). It is at this stage that the VC is formed. Due to the difficulty of positioning the wires

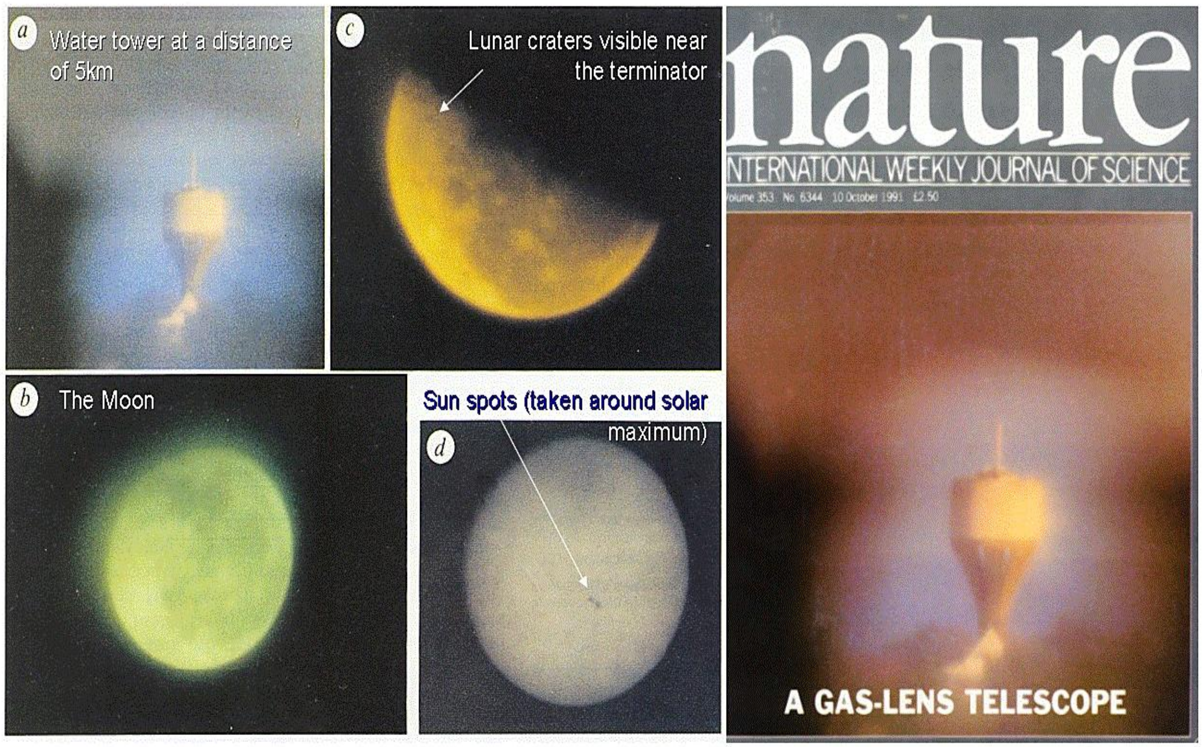


Figure 4. Water tower at 5 km, the Sun and Moon seen through a gas telescope.

with precision, only about 20 % of the implosions were satisfactory. However, we were able to demonstrate the formation of a sub-hundred micron diameter VC (Fig. 6b), which is what may be needed for laser acceleration experiments - as described in section C. Greater reliability will be obtained by substituting sets of electrodes in series for each wire. A new power supply, capable of producing the correct high voltage pulse is on order.

3.4. Flame driven gas lenses. (N.Nativel)

The focal length of tubular gas lenses is given by the semi-empirical formula

$$f = \frac{10^4}{6\ell} r^2 \frac{Tw}{Tw - 300}$$

where r is the radius of the lens, T_w is the wall temperature in absolute degrees and l is the length of the tube. This formula explains why gas lenses tend to be long narrow devices. In an attempt to remedy this negative aspect, we recently experimented with "flame lenses" in which flat oxyacetylene flames were injected into refractory or stainless steel cylinders (fig. 7a). (23). Although this method met with some success, the foci obtained were "fuzzy" due to turbulence and probably of little practical use. However, during our flame lens research, it happened that the flame was angled in the "wrong direction": fig. 7b. As explained in our submitted article, this produced a remarkably good focus. The resulting lens we call a "flame driven lens", since the flame only serves to heat the stainless steel structure to a high temperature as well as to entrain air through the lens in several non-turbulent modes.

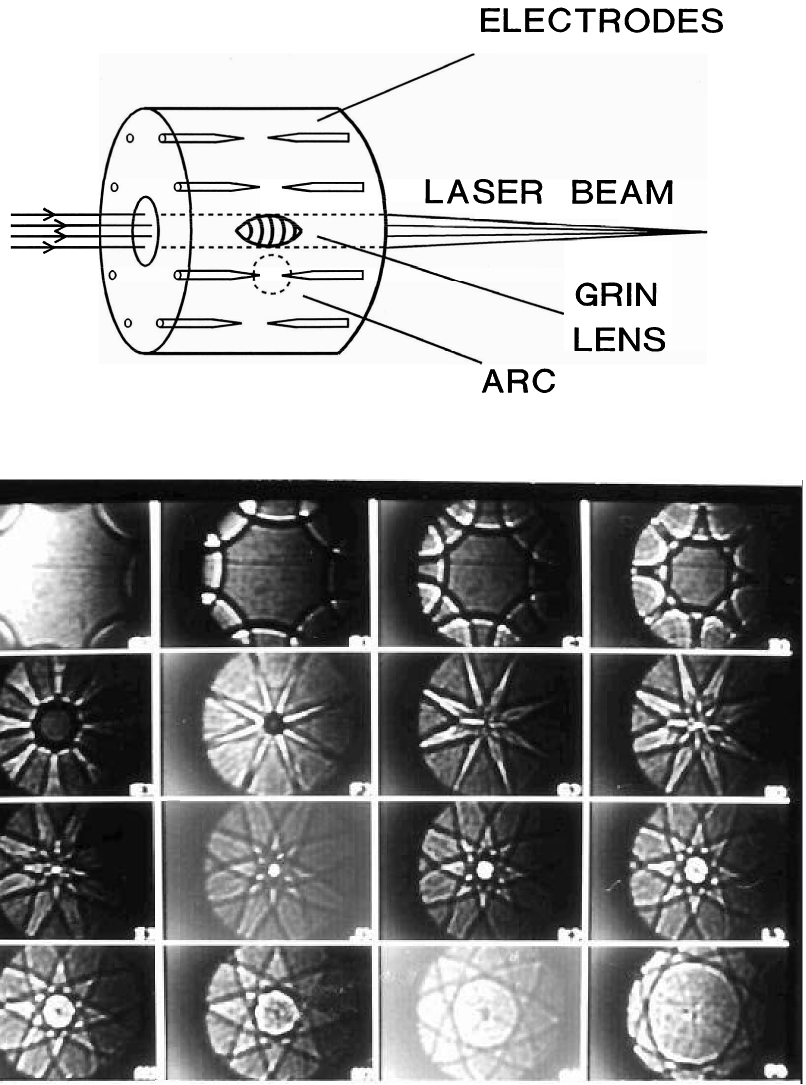
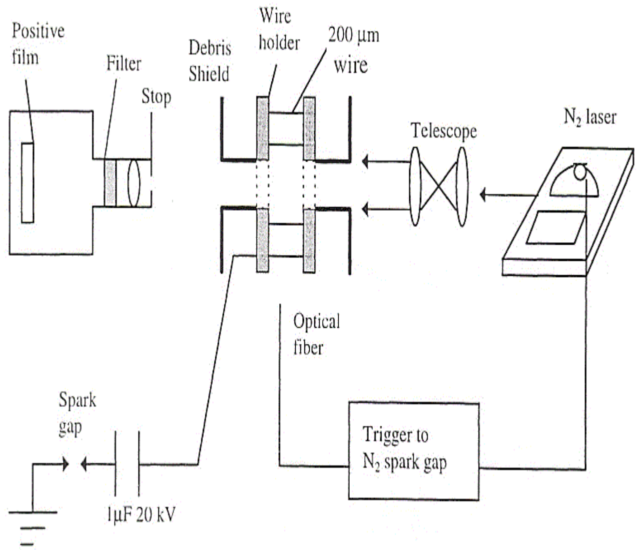


Figure 5. a) Device Geometry. b) Time sequence of CSL waves at times 3.2, 5, 6, 6.9, 8, 10, 10.4, 10.9, 11.3, 11.6, 11.8, 12.2, 12.4, 13.1, 14 and 15.6 μs.

4. SOME APPLICATIONS OF NSNRO.

4.1. Laser Propulsion with NSNRO and Varifocal Beam Control.

Laser propulsion has so far only been demonstrated up to a height of some 30m. in the record breaking Myrabo *et al.* experiments (24). For such low level flights, atmospheric absorption or distortion is hardly likely to be problematic - especially as the "fuel" was air itself. The Myrabo *et al.* "light-craft" is designed so it could accommodate the hollow beam from an unstable resonator CO_2 laser. Other "flyers" such as the Phipps *et al.* "Reference Flyer" (25) or the DLR Bohn and Schall bell shaped light-craft (26), may find Gaussian beams preferable. In South Africa, our early (1997) successful >5m flights (27) were made possible by the use of the low divergence MLIS (molecular laser isotope separation) Gaussian beam. On attempting to repeat this experiment more recently (2001) with a single one kilowatt oscillator (28), problems typical of future high altitude missions were encountered: beam distortion and absorption prevented the one gram light-craft from rising higher than two meters. This was because the poor quality of the beam compelled us to focus the light within the launch



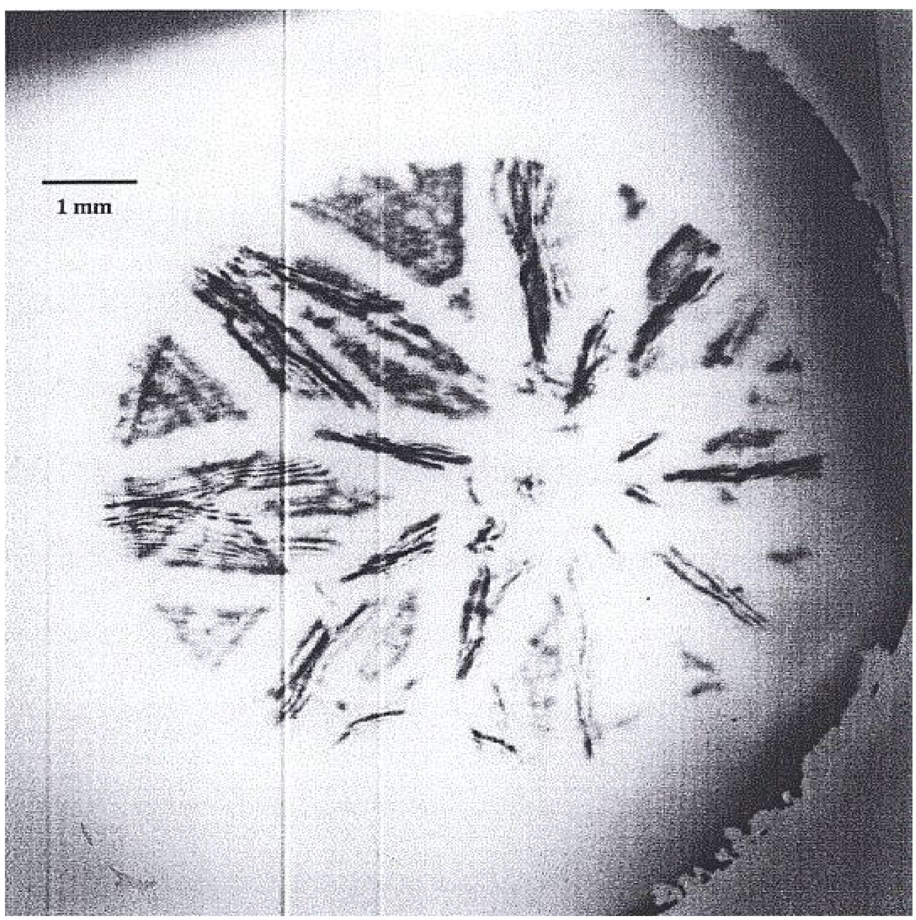


Figure 6. a) Optics of the experiment. b) Smallest pipe obtained after collision. Note the dark focal dot at the center of the pipe.

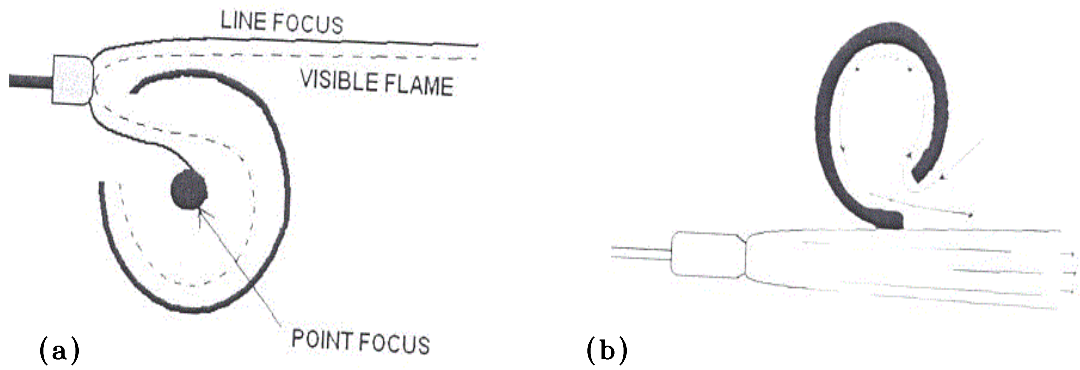


Figure 7. a) Directly injected flame lens produces fuzzy focus. b) Flame driven lens generates sharp focus. (Courtesy Optics and Laser Technology).

tube and to use a highly absorbing "fuel". (Without focusing and fuel change, the projectile failed to levitate). This focusing and fuel change resulted in combustion vapor-induced breakdown, once the craft had exceeded the focal height. Similar problems with "flyer" exhaust interacting with multi-megawatt average power beams will we believe, make varifocal beam control essential for "industrial scale" propulsion of the future. Many of the NSNRO lenses or mirrors described above could be useful. For centimetric beams either the CSL, the SPGL or the novel flame driven lens could ensure that the flyer is never too far from the focal region.

If as is likely for beams of multi-megawatt average power, one will be dealing with meter scale apertures, then "AO" and/or flexible mirrors may be the only varifocal options. For vertical flights, mercury mirrors should be considered. Also the same PCM or Four Wave Mixing Amplifier tricks used in laser fusion might prove useful in compensating for the atmospheric distortion of the beam. At the University of Natal, Cazalet *et al.* (29), demonstrated how a PCM could be used to remove the distortions of a gas lens. The disadvantage of using this method for laser propulsion is that because the optical path length through the atmosphere needs to be short and because of the long o.p.l. in free space, the trajectory would need to be steep as well as linear. The lightcraft would transmit a seed beam (similar to that envisaged in laser fusion) and would not be allowed to deviate from the amplified return beam which is fixed in space

4.2. Laser Fusion (LF).

LF is the one high power application where NSNRO has been routinely employed, namely in the aforementioned Nova plasma isolator. NIF and "Laser Megajoule" may fire at most a few shots per day (not many less than Nova, Omega and GEKKO). Running a future LF power plant at several Hertz and average powers of several MW will stress the optical components far beyond present day levels. Already the dimensions of petawatt and terawatt systems are determined by damage considerations. It is inevitable that lenses and mirrors that cannot be damaged - such as the totally forgotten Russian gas dynamic lens (Fig. 1g) - will play an important role. All LF plant designs address the problem of protecting the final focusing optics from debris. One popular concept is to use a gas blanket system to absorb the debris as well as to exhaust the chamber after the TN detonation. (30). Configuring the blanket system as a gas lens would reduce the aperture of the final optics from ca 50 cm to 10 cm and simultaneously remove the cost of periodically replacing damaged lenses or mirrors as well as reduce the radioactive waste.

4.3. Lithography and Virtual Capillaries (VC).

In order for the Moore's Law prediction that the micro-electronic component density double every two years (31) be realized, ever shorter wavelengths for lithography are becoming essential. Two plasma based methods are at the forefront of this industrial research. The first is laser produced plasma (LPP) as described in for instance I.C.E. Turcu's book on excimer LPP (32). The second is the now commercially available capillary or rotating electrode-pair discharge method, which generates EUV light at the mandatory 13.5 nm wavelength. The rep. rate of the commercial sources is a few tens of Hertz, the useful power ca. 20 W , and the mirrors are 90 % reflecting multilayer silicon-molybdenum. Debris mitigation is an important aspect and is accomplished with a gaseous layer (not unlike future LF). Capillary EUV sources are only 1 cm to 1.5 cm long and can be operated at kHz. rep. rates in a research environment. Commercial sources have a life-time of over 1000 hours. One of us (AC) has suggested that virtual capillaries should be studied in the Moore's Law context: debris and life-time problems could be greatly reduced. We have demonstrated that the capillaries can be narrow enough. Yet to our knowledge, no laboratory has operated a VC so that it emits light, let alone under conditions similar to the EUV sources.

4.4. Laser Accelerators and Virtual Capillaries.

The "magic formula" for maximum laser acceleration energy versus electron density (9) is

$$E\,(eV) = \sqrt{n_e}\,(cm)^{-3/2}$$

This says that if multi-GeV beams are required for instance for manufacturing positron sources for PET (positron emission tomography), then acceleration lengths of tens of centimeters will be needed and high plasma densities ($n_e \approx 10^{20}$ cm^{-3}). This demands some form of high density laser wave-guiding through narrow channels. As with lithography, whilst pre-excited capillary wave-guiding works well for a limited number of shots, this is only a useful method for proof of principle demonstrations. It may not be easy as our preliminary VC experiments taught us, to produce a reliable high rep-rate sub-millimetric VC. But it will be equally difficult to imagine multi-staging and synchronizing air jet petawatt laser acceleration regions, not to mention "getting the phase right". This may involve gas jet positioning with sub-micron precision. In the event of the phase adjustment problem proving insuperable, it may be better to opt for the longer interaction lengths provided by plasma pinches, self drilled plasmas or VC's. This may also require a different acceleration mechanism such as Beat Wave Acceleration. In this context we mention an unusual feature of virtual capillaries, namely that their transverse and longitudinal geometry is easily modified. By exploding only four wires we have already demonstrated a VC with rectangular cross section (22). It would be a trivial modification for the spark gap driven VC to generate a VC light pipe that follows a circular trajectory. Coupled with an adjustable magnetic field, this would enable "optical cyclotron" (or "cycloptron") experiments to be conducted. The prototype optical cyclotron could be of similar size to E.O.Lawrence's first ever device which only generated 50 MeV electrons. If the cyclotron radius $r \simeq 20$ cm and the VC radius is 100 μm then for the circular light guide we write for the arc length

$$l = r.\Delta\theta$$

and

$$\Delta\theta = l\frac{\Delta n}{\Delta r}$$

so

$$\frac{\Delta n}{\Delta r} = \frac{1}{r} \qquad \text{or} \qquad \Delta \mathrm{n} = \frac{\Delta \mathrm{r}}{\mathrm{r}} \approx 5.10^{-4}$$

Since

$$n \approx 1 - \frac{1}{2}\frac{n_e}{n_c}$$

And for 1 μm light $n_c \approx 10^{21}$ cm^{-3} we require $n_e \approx 10^{18}$ cm^{-3}, an easily achievable light pipe requirement.

4.5. High power laser beam delivery for Laser Isotope Separation (AVLIS and MLIS): rotating and aerodynamic windows.

Uranium, though probably the most important IS material is not the only material of interest. Presently there is great importance attached to growing pure carbon 12 diamond for semi-conductor manufacture (19) because of its very high thermal conductivity. (Absence of phonon scattering). But whatever the material, whatever the laser, very long thin high intensity beams will probably be required for industrial scale operation. This means that the optics will need to be able to withstand average powers in the kilowatt/cm^2 range. Thermal lensing in transmission optics is well known and well documented in the literature. In high power laser systems such as the Pelindaba CO_2 MLIS chain, this thermal lensing leads to rapid changes in the measured beam parameters observed at the amplifier chain output. An example of this is shown in fig. 8 where the beam radius is observed to rapidly decrease with time as the thermal lens develops. Such rapid laser beam changes can result in catastrophic damage to optical elements further down the path, create non-linear effects such as self-focusing, or generate plasmas in air. These influences are undesirable when trying to deliver high average power laser beams. There are two types of window that can mitigate the effects of thermal lensing: the rotating and the aerodynamic window. The rotating window is a device in which the optical window is rotated off axis, causing the beam to heat a different part of the window with each pulse. Care needs to be taken to achieve maximum heat dissipation. For example, if the rotation period matches the time between pulses, the window appears stationary. At the correct rate of rotation, the heating is spread over a large area thus reducing the temperature gradient. Fig. 9 shows how significant reduction of thermal lensing was achieved in one of the MLIS amplifiers.

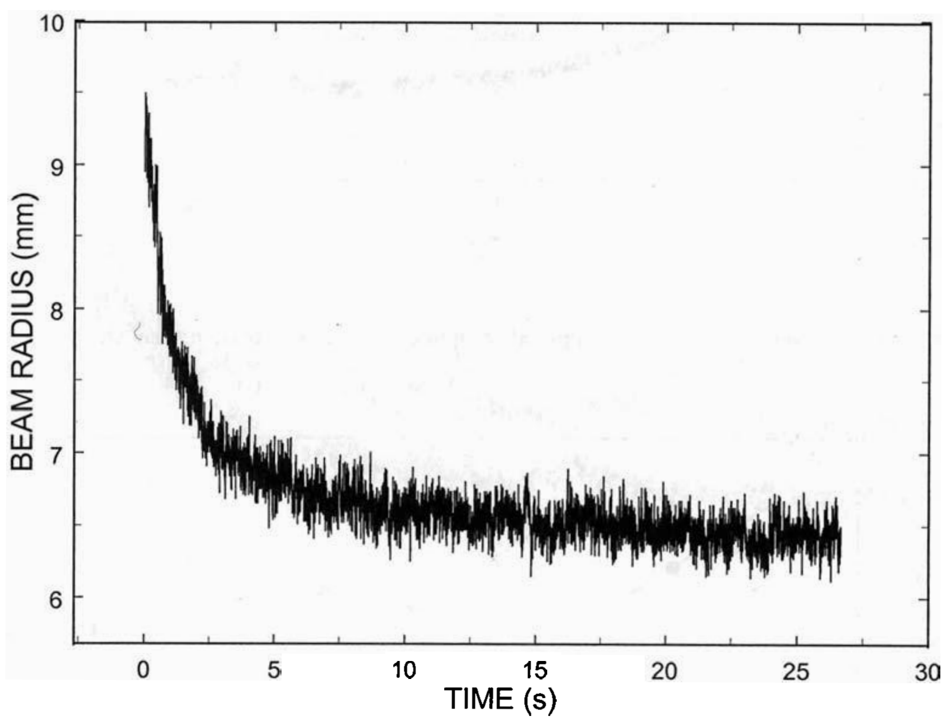


Figure 8. Change of laser beam radius in the MLIS, MOPA chain. Stability is reached after approx 20s.

The aerodynamic window seeks to remove lensing by virtue of the absorption coefficient of gas being much lower than that of a solid state device. It uses flowing gas to act as a window: with the correct pressure gradients along the flow direction, the system acts as a barrier to the atmosphere. In our experiments, the flow of gas was parallel to the laser beam propagation direction, though in other designs transverse flow is employed. In this experiment , the last amplifier in the laser chain had both conventional windows removed and replaced with a

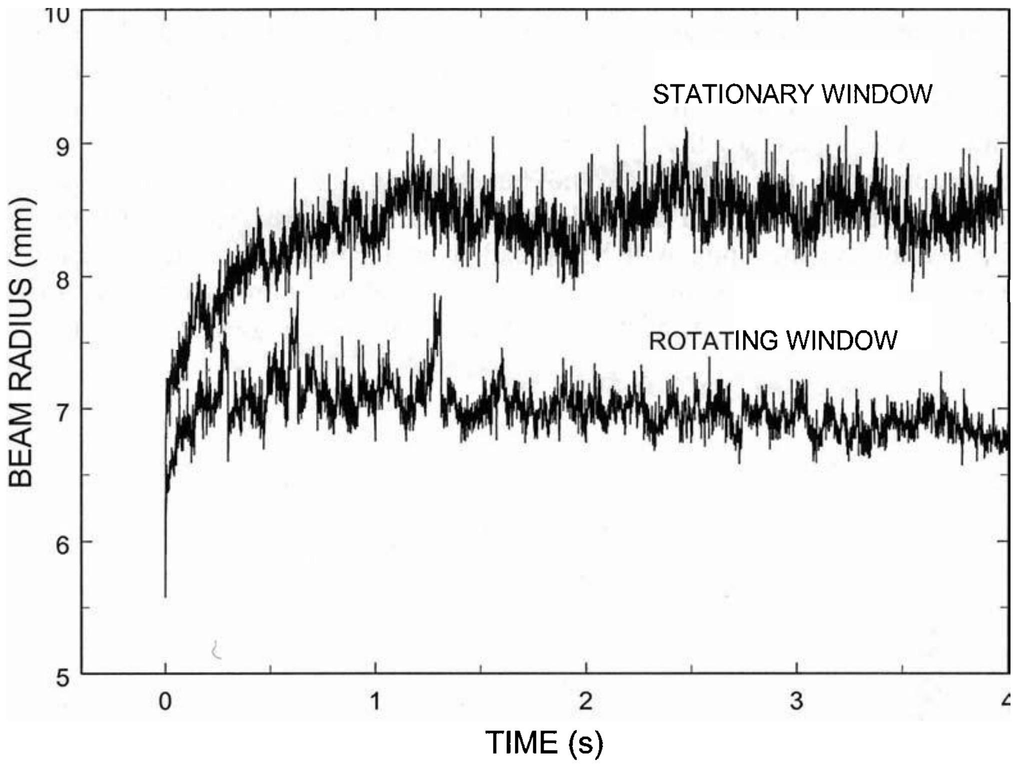


Figure 9. Significant reduction in thermal lensing achieved with a rotating window.

rotating window on the entry side and an aerodynamic on exit. Propagation through an amplifier with normal ZnSe coated windows was compared with combinations of rotating and aerodynamic windows: fig.10. The laser wavelength, pulse energy and rep. rate were 10.6 μm, 600 mJ, 300 Hz respectively for a Gaussian transverse mode. The aerodynamic window seems to offer significant benefits in reducing thermal lensing - much more so than with the rotating window: the beam radius is somewhat larger than when the aerodynamic window is not used. Also evident is the larger variance in beam measurements: - 0.4 mm with aerodynamic windows compared to 0.2 mm without. While the aerodynamic window reduces thermal lensing, there is another feature, not obvious from the above data. Measurements of the pointing stability of the beam after the aerodynamic window show that the lateral movement of the beam is increased and varies considerably more on a shot to shot basis than a beam through an ordinary window would. Measurements show that the average movement off center by the beam without the aerodynamic window is 0.24 mm, with a variance of 0.64 mm. With the aerodynamic window in place, the average movement is 0.8 mm, with a variance of 1.2 mm. The large variance is due to changes on a shot to shot basis. Aerodynamic flow in the window is somewhat unstable, with fluctuations causing beam movement. Similar fluctuations have been observed in most gas lens and gas jet devices and should be taken into account when comparing them with solid state optics.

5. CONCLUSION.

Non-solid or non-rigid optics are still only encountered in research laboratories. The need to provide high average power beams for laser propulsion, laser fusion, laser fast ignition, lithography, laser accelerators and laser isotope separation may change this situation. We have pointed out that a great range of NSNRO exists.

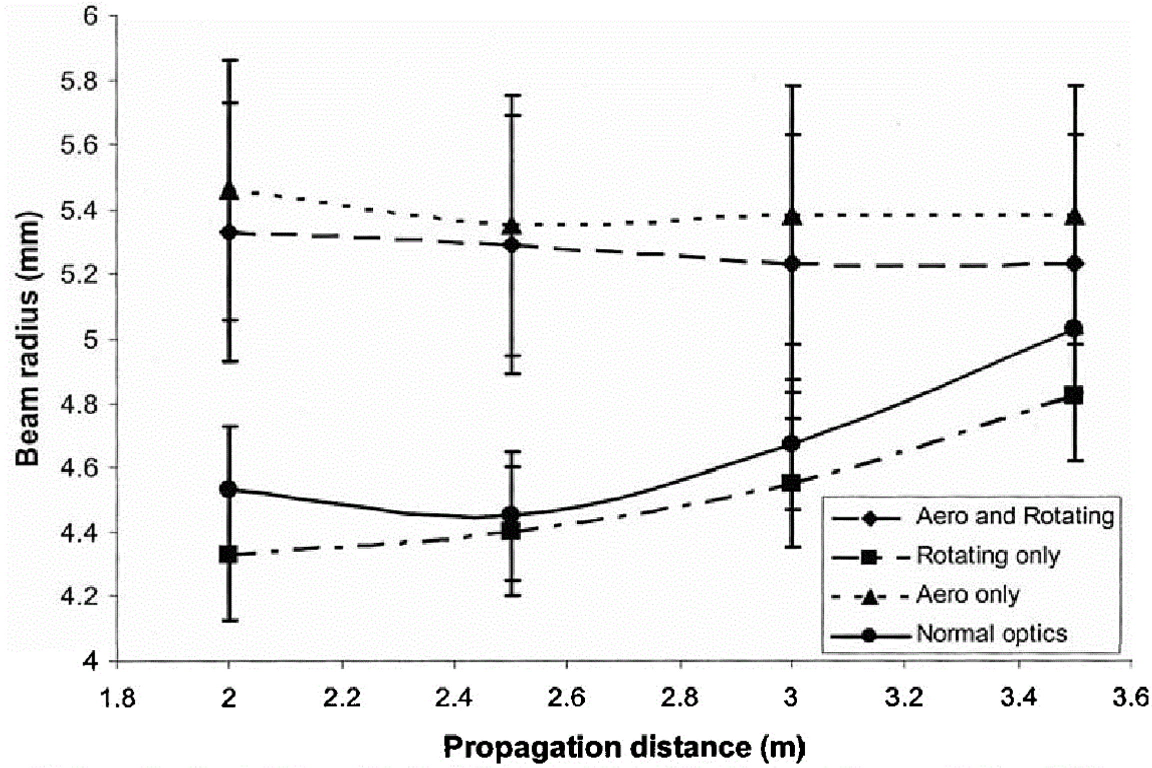


Figure 10. Beam radius for various window combinations.

REFERENCES

1. R. Hellwarth, 1977. J.Opt.Soc.Am., 67, 1.
2. A. Yariv, 2000. IEEE Sel. Topics in Q. Electron., 1478.
3. D. Marcuse, 1982. "Light Transmission Optics". Van Nostrand. NY.
4. D. Gloge, 1968. "Deformation of Gas Lenses by Gravity". Bell Syst. Techn. J.4, 7, p. 179.
5. O. G. Martynenko, N. I. Lemesh. Il Nuovo Cimento, 5D (1985), 225.
6. E. Sinkiewicz, 1981. Optica Applicata, 11, p. 243.
7. P. T. Rumsby, M. M. Michaelis, 1977. Opt. Comm., 21, 337.
8. C. L. M. Ireland, 1980. J.Phys.D: Appl.Phys., 13, 9.
9. R. Bingham, J. T. Mendonca, P. K. Shukla, 2004. Plasma Phys. & Contr. Fusion. 46, R1.
10. S. Banerjee *et al.*, 2003. J.Opt.Soc.Am. B., 20, 182.
11. H. Fiedorowicz, 2005. Laser and Part.Beams, 23, 365.
12. P. A. Norreys *et al.*, 2003. 3rd Int.Conf. on Inertial Fusion Sci & Applics. 13.
13. N. Lopes, 2004. CARE-ELAN 2004-017. "Adv and Novel Accelerator Development". GoLP Presentation A10.
14. T. Hosokai *et al.*, 2003. Phys Rev E.67.036407. (See also JAERI website).
15. H.-C. Wu *et al.*, 2005. Laser and Part.Beams, 23, 417.
16. H. C. Kapteyn *et al.*, 1991. Opt.Lett., 16, 490.
17. M. J. Shaw *et al.*, 1986. J.Opt.Soc.Am.B., 10. 1466.
18. M. Notcutt, 1989. "Gas Lenses". Ph.D. thesis, University of Natal, South Africa.
19. A. R. Prause, 1994. "Applications of Optical, Plasma and Laser Focusing". Ph.D. thesis, University of Natal, South Africa.

20. M. M. Michaelis *et al.*, 1991. Nature, 353, 547.
21. R. Buccelato, N. Lisi and M. M. Michaelis, 1993. Opt. Comm., 101, 350.
22. A.Conti. 2004. "Gas and Plasma Structures". Ph.D. thesis, University of KwaZulu-Natal, South Africa.
23. M. M. Michaelis and N. Nativel, 2006. Optics and Laser Technology, submitted.
24. L.N. Myrabo, 1987. SDIO Workshop on Laser Propulsion. P 173-208.
25. C. R. Phipps, J. P. Reilly, J. W. Campbell, 2000. Laser and Part. Beams, 661.
26. W. O. Schall, W. L. Bohn, H. A. Eckel, W. Mayerhofer, W. Riede, E. Zeyfang. HPLA III. Proc. SPIE, 4065, 472.
27. M. M. Michaelis *et al.*, HPLAIV. Proc. SPIE, 4760, 691.
28. M. M. Michaelis and A.Forbes, 2006. Submited to S.A.J. Sci.
29. R. S. Cazalet, P. F. Cunningham *et al.*, 1990. Sci. Tech. (J.Phys.E), 1, 147.
30. N. G. Basov, I. G. Lebo, V. B. Rozanov. "The Physics of Laser Thermonuclear Synthesis" in Russian. (Translation available).
31. H.Wong, H,Iwai. 2005. Physics World. Sept. 40.
32. I. C. E.T urcu. 1996. "Generation & Application of X-Rays from excimer's". D.Phil thesis. London.