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**Technical Report**
RAL-TR-95-029

# HCM Large Facilities Access Programme The Sodium-like Copper Recombination X-ray Laser

**E E Fill et al**

July 1995

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# The Sodium-like Copper Recombination X-ray Laser

# An experiment performed with funding from the HCM Large Facilities Access Programme

# Access to the High Power Laser Facilities at the Rutherford Appleton Laboratory

# Contract CHGE-CT93-0032

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## INTRODUCTION

Funds allocated under the HCM Large Facility Access Programme are available to provide access for European researchers to the VULCAN and Sprite high power laser systems situated within the Central Laser Facility at the Rutherford Appleton Laboratory. This report details the first experiment selected for scheduling under this contract carried out in Oct/Nov 1994.

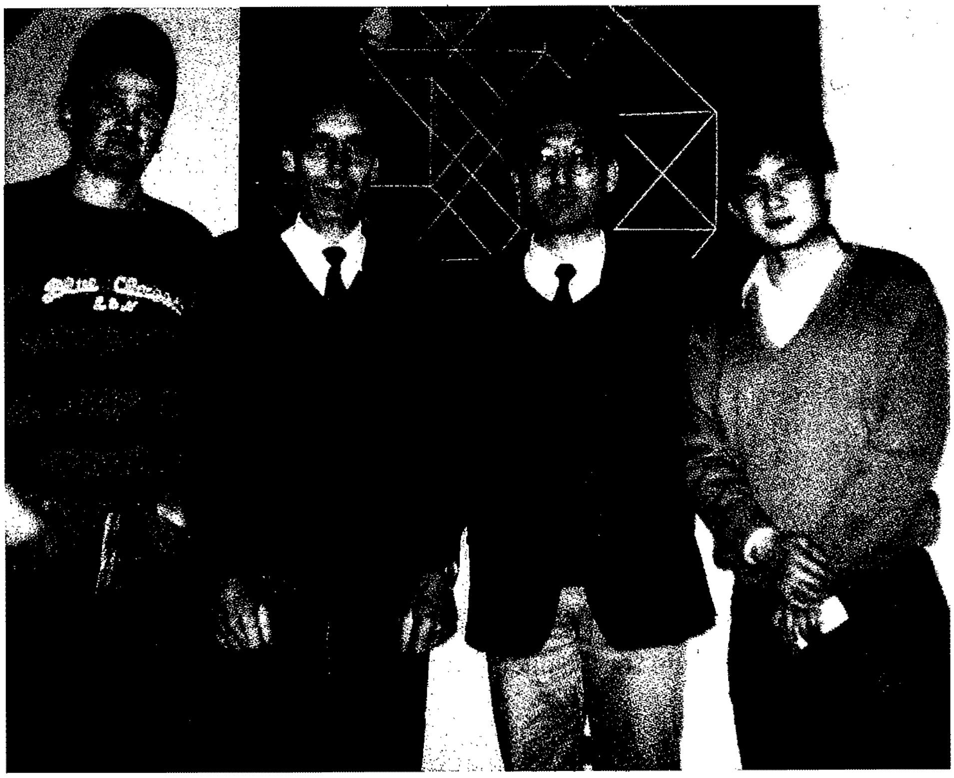



Figure 1. Part of the experimental team.
From left to right: Dr Dieter Schlögen, Prof. Ernst Fill, Prof. Jie Zhang and Dr Yuelin L Li.

The experiment was proposed and led by Prof. Ernst Fill and a visiting team of young researchers from the Max Plank Institute supported by the UK X-ray laser consortium, coordinated for these experiments by Prof. Jie Zhang of the University of Oxford.

**Experimental Objectives**

- To investigate the possibility of achieving high gain operation in Na-like copper x-ray lasing at 111 Å using ultrashort laser pulses
- To study the different plasma conditions generated by ns and ps laser pulses
- To observe the spatial distribution of plasma emission and hence investigate the size and location of the gain region
- To obtain information on plasmas suitable for Li-like x-ray lasing scheme

## Recombination X-ray Lasers

One of the primary objectives in x-ray laser research is biological applications in the so-called water window around 22-45 Å [1]. An X-ray laser microscope could provide higher resolution than optical instruments and avoid much of the often destructive specimen preparation needed for electron microscopy. X-ray laser holograms of biological structures within living cells would be an invaluable aid for investigating their functions. The brightness and coherence of an X-ray laser source is essential for this work.

The recombination scheme operating with adiabatic cooling is in principle more favourable than the collisional pumped scheme in extending x-ray lasers to shorter wavelengths, because the recombination scheme requires a much lower driver energy. Systematic studies suggest that the interaction of fibre targets and picosecond (ps) laser pulses produces heating at close to solid density, thus enhancing the cooling by adiabatic plasma expansion. The rapid plasma cooling generates conditions suitable for producing high gain in recombination lasers [2,3]. There is therefore reason to believe that it is possible to reduce the driver energy for x-ray lasers considerably by using ps high brightness laser pulses. Towards this goal, a series of experiments were conducted at RAL. An exceptionally high gain was recently demonstrated on the hydrogen-like carbon 3-2 transition at 18.2 nm using 20 J, 2 ps pulses focused on 7 μm diameter carbon fibres [4].

Lithium-like and sodium-like ions are analogous to the hydrogen-like ions, having one electron in the outer atomic shell but one or two closed inner atomic shells. For lasing transitions, lithium-like and sodium-like ions have somewhat higher quantum efficiency. Amplification has been observed for many transitions both in lithium- and sodium-like ions using nanosecond (ns) driver pulses [5,6]. With a view to the possible extension of high gain recombination x-ray lasers to shorter wavelengths, sodium-like copper was chosen for the present investigation. We report experimental evidence of high gain in a sodium-like copper recombination x-ray laser driven by 20 J, 2 ps pulses from the chirped pulse amplification (CPA) beam on the VULCAN laser facility.

## Plasma Emission from ns and ps Pulses

There is growing interest in the interaction of ps or fs pulses with matter, owing to the advent of short-pulse high-power lasers based on chirped-pulse amplification. In particular, more and more work is devoted to generating laser-produced plasmas with such pulses, in view of the variety of applications such as laser fusion, short pulse x-ray emission and x-ray lasers [7, 8].

While the generation of x-rays by ns laser plasmas is well investigated, and a considerable amount of work has also been expended on investigating x-ray emission from ps laser plasmas, only a few studies are devoted to comparing x-ray spectra generated by different pulse durations.

Short (ps or fs) laser pulses can significantly heat targets before any expansion occurs generating close to solid density plasmas. This is in contrast to the interaction of ns long pulse with targets where the main heating occurs at densities close to the critical density. Consequently, the densities of ps laser plasmas can be orders of magnitude higher than those of ns laser plasmas. The enormous difference in the densities changes the dominance of the various plasma processes which control the population distribution within the atomic levels and therefore the spectra of the plasma emission. Comparison of plasma emission generated by ns and ps laser pulses would provide better understanding of different plasma physics in the ns laser plasmas and ps laser plasmas.

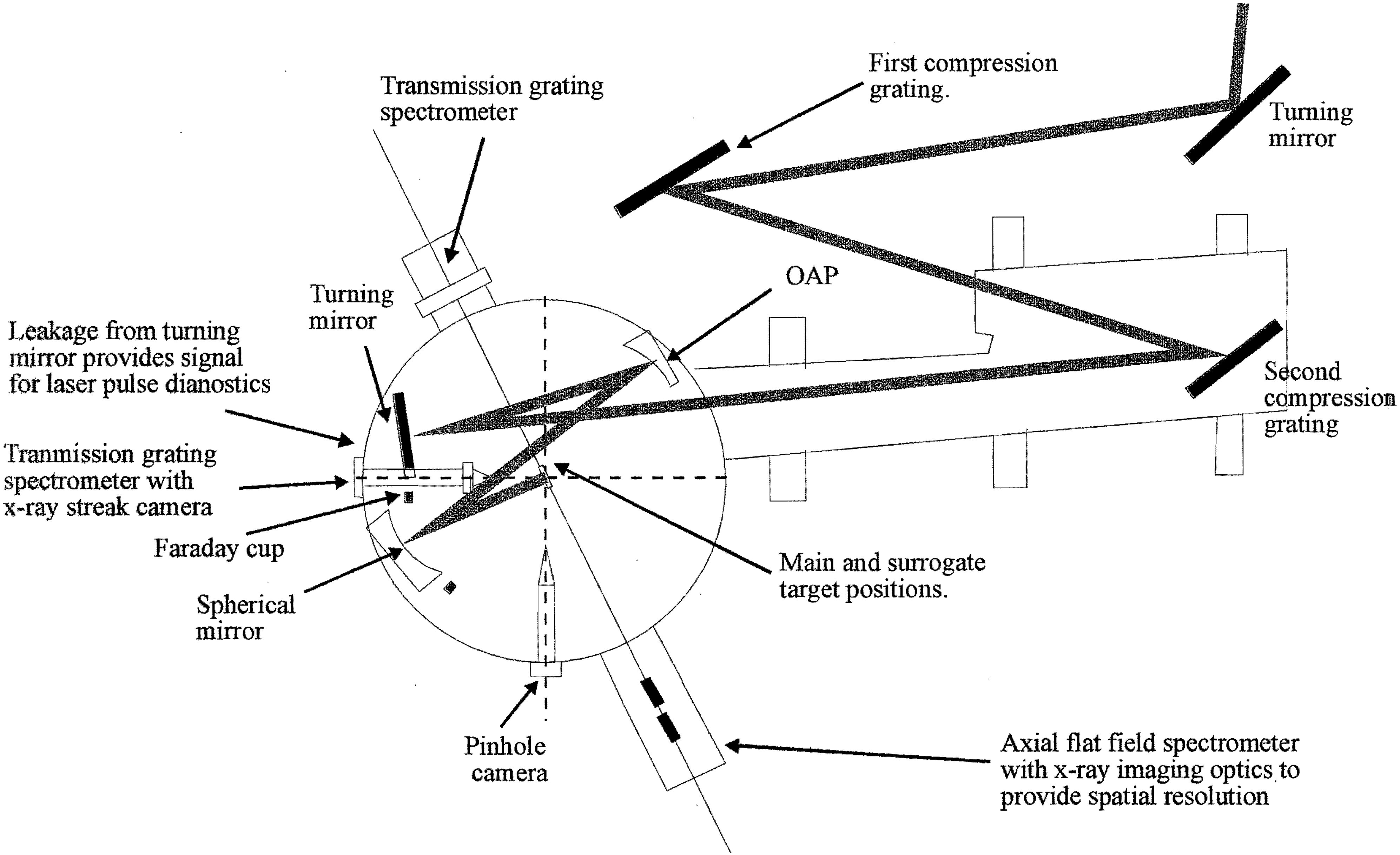
In this report we present a comparison of plasma emission in the region 60 Å < λ < 220 Å generated by 1 ns and 2 ps laser pulses, with similar pulse energies. Thus, the intensities applied to the target differed by a factor of up to 500. The investigations were made with moderately high intensities up to $1 \times 10^{13}$ W/cm$^2$ for 1 ns and $5 \times 10^{15}$ W/cm$^2$ for 2 ps pulses.

## Experimental Set-up

The Central Laser Facility is ideally placed to carry out the proposed experiments. The VULCAN high power Nd:glass laser is extremely versatile, routinely operating with both ultra-short subpicosecond and nanosecond pulses to target. The subpicosecond pulses are generated using chirped pulse amplification [9, 10], where the pulse is stretched to ~250 ps using a double passed diffraction grating pair, amplified, avoiding the power limitations in the laser system, and subsequently recompressed in the interaction chamber. Peak powers in excess of 30 terawatts have been obtained in a pulse of 700 fs duration. With both the long and short pulse the prepulse intensity to target is < $10^{-6}$ of the intensity of the main pulse, an important consideration for these experiments.

A schematic of the compression and interaction chambers are shown in figure 2. The stretched pulse is incident onto the first grating which is outside the interaction chamber. The compressed pulse is then transmitted to target using all reflective optics. The first mirror allows a 5% sample of the beam to be transmitted for compression diagnostics. The 2ps CPA beam is reflected by an f/3 off-axis parabolic mirror to a spot focus which is imaged by an f/3 off-axis spherical mirror to produce a line focus 7 mm long and 20μm wide.

Figure 2: Set-up for the Na-like Cu Recombination X-ray Laser Experiment



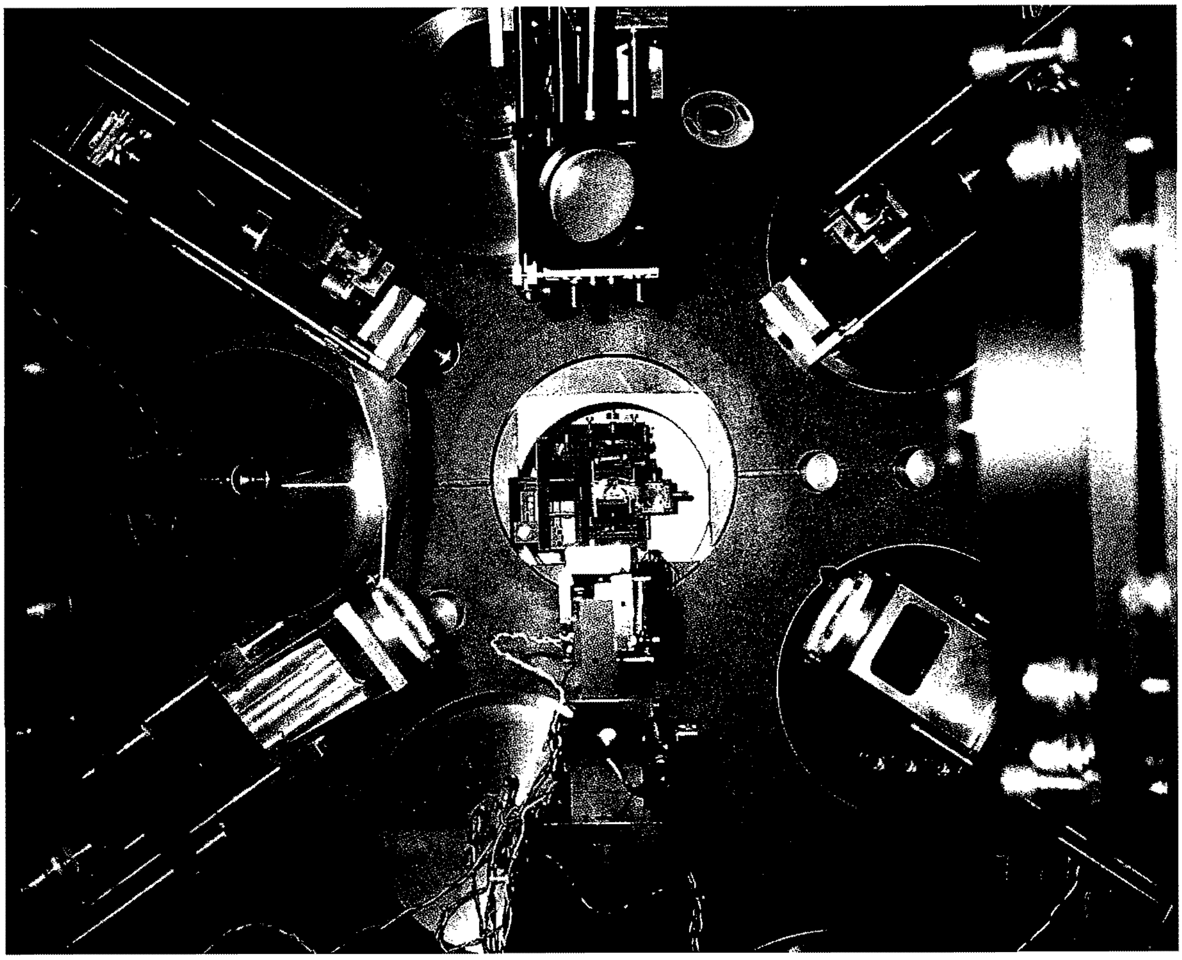


Figure 3. This photograph shows a view along the x-ray laser axis used during the experimental investigation. In the centre of the image the specialised flat-field imaging spectrometer which measures the spatial location of the gain region within the plasma plume can be seen. The four arms of a high resolution split-field microscope (pointing from the corners of the image to the centre) can also be observed. This unique alignment system was required to position the very thin fibres within the high intensity region of the line focus.

## Dissemination of results

Several papers and reports have been or are in the process of being published. A list of the these is presented below. The material is also to be presented at the Euroconference: The International Research Workshop on the Generation and Application of Ultrashort X-ray Pulses - II, in Pisa in September, an important forum for this work.

## Publications

1 E E Fill, J Zhang, Y Li, D Schlögel, J Steingruber, C Danson, A Demir, M Holden, M H Key, C L S Lewis, A G MacPhee, P A Norreys, G J Tallents, F Walsh and P Zeitoun. Soft x-ray emission of ns and ps laser plasmas from fibre targets illuminated by multi-terawatt laser pulses, Submitted to Phys. Rev. E.

2 J Zhang, E E Fill, Y Li, D Schlögel, J Steingruber, C Danson, A Demir, M Holden, M H Key, C L S Lewis, A G MacPhee, P A Norreys, G J Tallents, F Walsh and P Zeitoun Ultrashort pulse driven Na-like Cu recombination x-ray laser, (in preparation).

3 M Holden, G J Tallents, A Demir P Zeitoun, J Zhang, E E Fill, Y Li, D Schlögel, J Steingruber, C Danson, M H Key, C L S Lewis, A G MacPhee, P A Norreys and F Walsh Spatial characteristics of ultrashort pulse driven plasmas, (in preparation).

## Laboratory Reports

1 J Zhang, E E Fill, Y Li, D Schlögel, J Steingruber, C Danson, A Demir, M Holden, M H Key, C L S Lewis, A G MacPhee, P A Norreys, G J Tallents, F Walsh and P Zeitoun Evidence of high gain in a sodium-like copper x-ray lasing at 111 Å, Annual Report of Central Laser Facility, Rutherford Appleton Laboratory, 1995.

2 E E Fill, J Zhang, Y Li, D Schlögel, J Steingruber, C Danson, A Demir, M Holden, M H Key, C L S Lewis, A G MacPhee, P A Norreys, G J Tallents, F Walsh and P Zeitoun Comparison of plasma emission generated by ns and ps laser pulses, Annual Report of Central Laser Facility, Rutherford Appleton Laboratory, 1995.

## Conference Presentations

1 G Tallents et al., International Research Workshop on the Generation and Application of Ultrashort X-ray Pulses, 20-23 Sept 1995, Pisa, Italy.

2 J Zhang et al Invited talk, International Workshop on X-ray Lasers and Optics, 11-14 Sept 1995, Mianyang, China.

3. E E Fill et al, Invited talk, SPIE's 40th Annual Meeting, 9-14 July 1995, San Diego, USA.

## EXPERIMENTAL RESULTS

### (i) Evidence of High Gain in a Sodium-like Copper X-Ray Laser at 111 Å

The spatially averaged incident irradiance in the 7 mm line focus was $(5 \pm 1) \times 10^{15}$ W/cm$^2$ for the data discussed here. The targets used in the experiment were copper coated (thickness typically > 3000 Å) carbon fibres of 1 cm length and 7 μm diameter supported at one end. They were positioned better than ±2 μm spatial accuracy and ±1 mad angular accuracy using a split-field microscope system. The free end of the target was placed well within the line focus to avoid creating a cold output end in the plasma, and the irradiated length was varied by moving the line focus axially along the fibre which was always at the same location.

Two soft x-ray spectrometers viewed the line plasma in the axial direction from both sides as the primary diagnostics. One of the spectrometers was a flat-field grazing incidence soft x-ray spectrometer with a 1200 line/mm aperiodically ruled grating. The detector was an x-ray sensitive phosphor screen coupled to a charged-coupled device (CCD). The other spectrometer was a 5000 line/mm transmission grating. The length and the spatial homogeneity of the line focus were monitored by means of an x-ray pinhole camera, which viewed the line focus at 45 degree from above. A KAP crystal spectrometer was used at 45 degree to the fibre axis to measure the ionisation balance of the plasma.

A series of spectra from the on-axis flat-field spectrometer are shown in figure 4. The spectra correspond to three irradiated lengths of copper fibres: a) 2.3 mm, b) 3.3 mm, c) 4.6 mm respectively. In these spectra, only the strong 5g-4f line emission was observed. This is contrast to steady state ablation from either fibre or slab targets with long pulse (nsec) driver lasers where all of the four possible gain lines (5g-4f, 5f-4d, 6g-4f and 6f-4d) appear (figures 5 & 6). Similar features were observed in the spectra of iron fibre targets irradiated in the experiment. The irradiated intensity on fibres for the data in figure 4 was around $5 \times 10^{15}$ W/cm$^2$, at which there were mainly neon-like resonance lines and only comparatively weak fluorine-like and oxygen-like lines in the crystal spectra. This plasma ionisation is near optimum for a sodium-like copper recombination laser according to the simulation result [11].

There is strong continuum emission background in the 2 ps spectra, compared with the ns spectra (figures 5 & 6). This maybe attributed to the ps pulse produced higher density at which the maximum electron temperature is reached. The higher density leads to a larger effects of opacity, line broadening etc. To suppress the strong continuum emission from the part close to the target surface, spectra in figure 4 were integrated over the spatial region in the radial direction with r > 50 μm from the target surface.

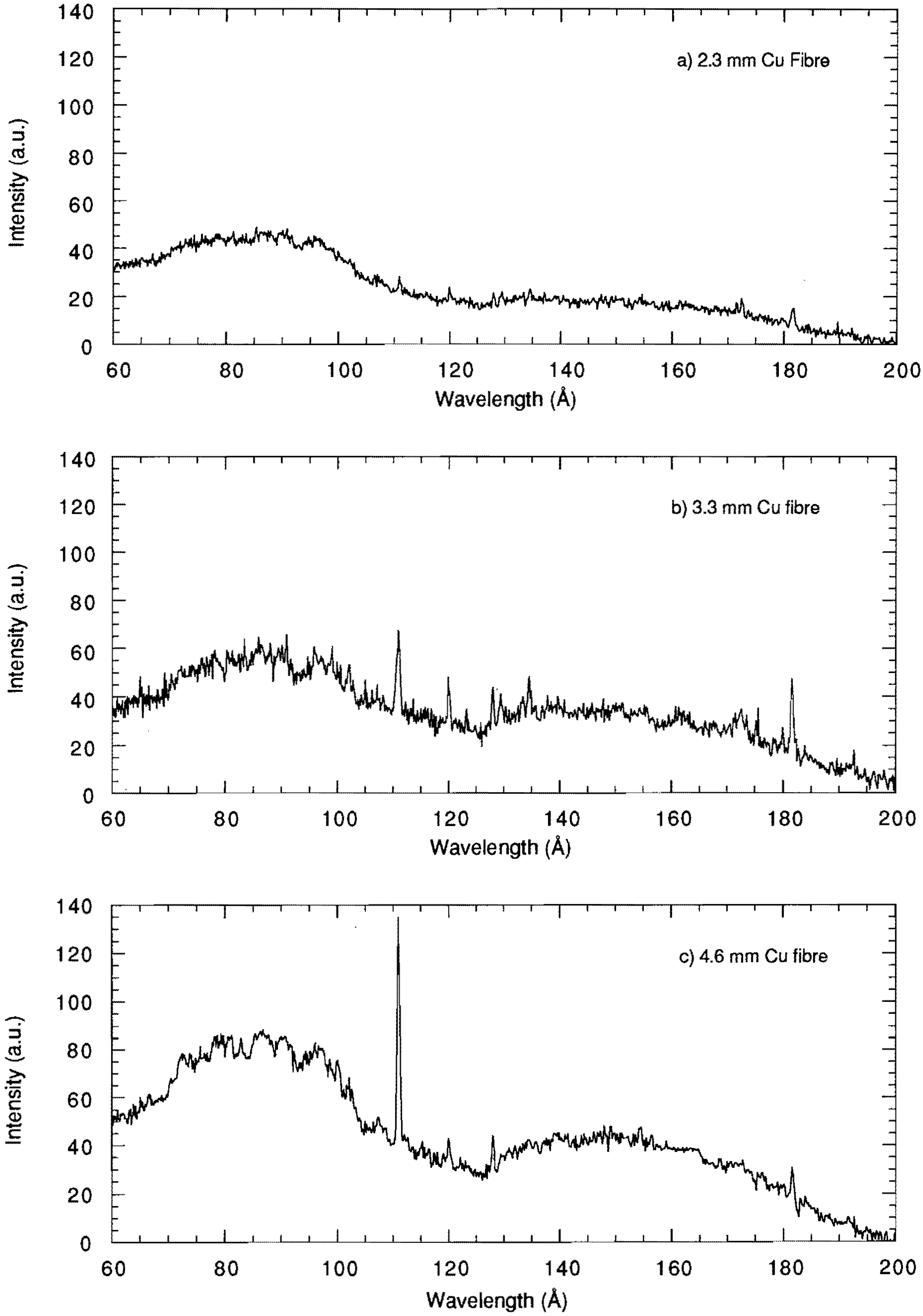



Figure 4. On-axis spectra of the copper fibre target with (a) 2.3, (b) 3.3, and (c) 4.6 mm lengths irradiated by 20 J, 2 ps laser pulses.

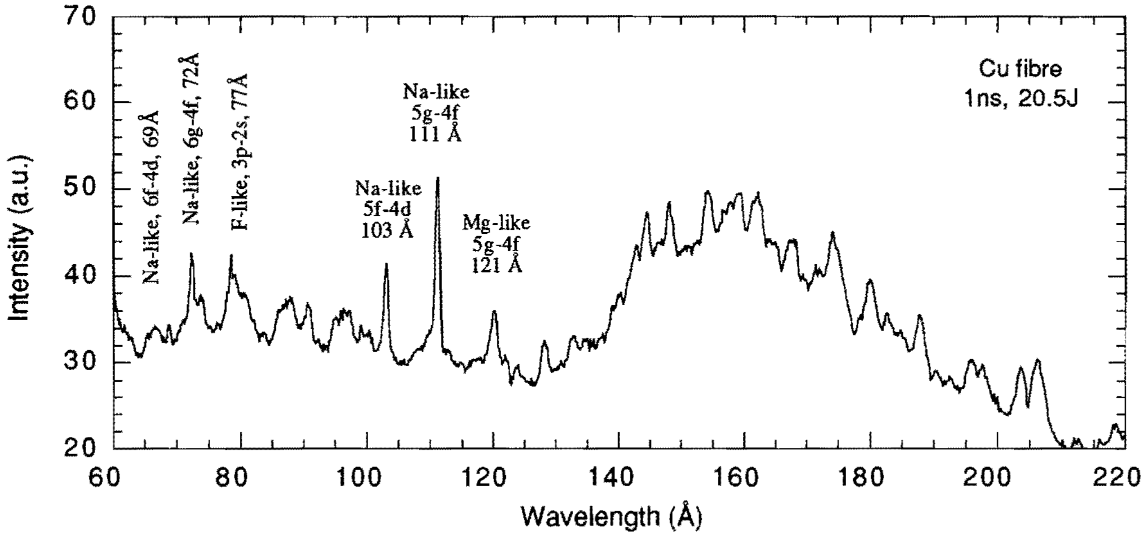



Figure 5. On-axis spectra of the copper fibre target irradiated by 20 J, 1 ns laser pulses.

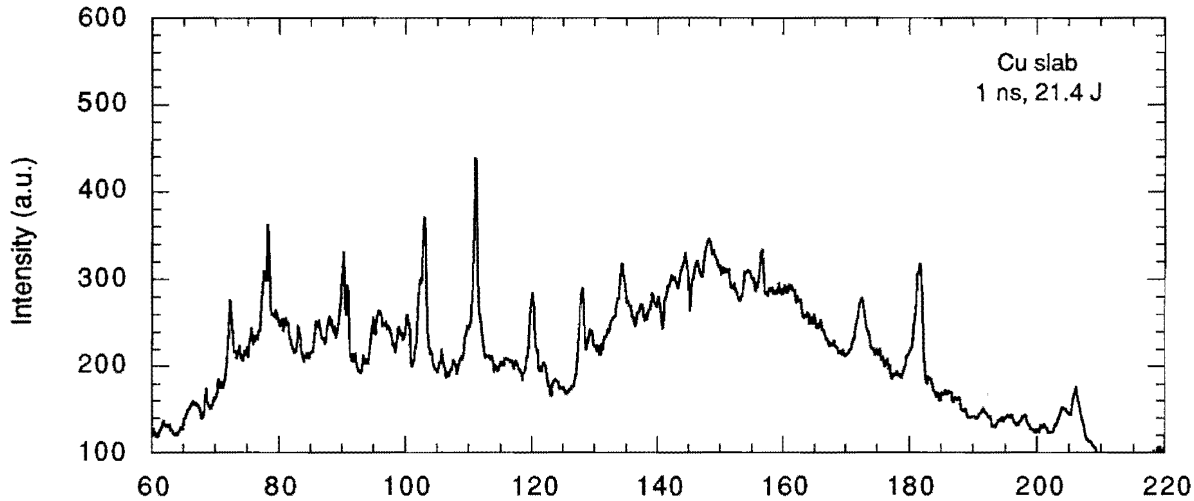



Figure 6. On-axis spectra of the copper slab target irradiated by 21 J, 1 ns laser pulses

The intensity of an individual line was obtained by subtracting the background continuum level and integrating spectrally and spatially over the spatial region with r > 50 μm in the radial direction.

At very short length, the 5g-4f line transition at 111 Å is very weak compared with the continuum background emission. The intensity of this line emission increased with the plasma length non-linearly. This line emission became dominant in the spectra for longer targets, giving a strong indication of stimulated emission on the 5g-4f transition. The results of these measurements were plotted in figure 7. The intensities of different shots on different detectors were cross-calibrated by the continuum emission, which increased linearly with the plasma length. The gain coefficient was estimated by least squares fitting of the Linford formula to the data giving 8.8 ± 1.4 $cm^{-1}$.

The fibre targets were fabricated by coating 7 μm diameter carbon fibres with a layer (thickness > 300 nm) of copper. It turned out that the coating process frequently resulted in bending of the fibre targets. As a result, the longest straight length of the coated fibre targets was limited to 5 mm by the coating process. It has however been found out after the experiment that longer straight copper coated fibres could be manufactured by sputtering cold copper ions into the surface layer of carbon fibres.

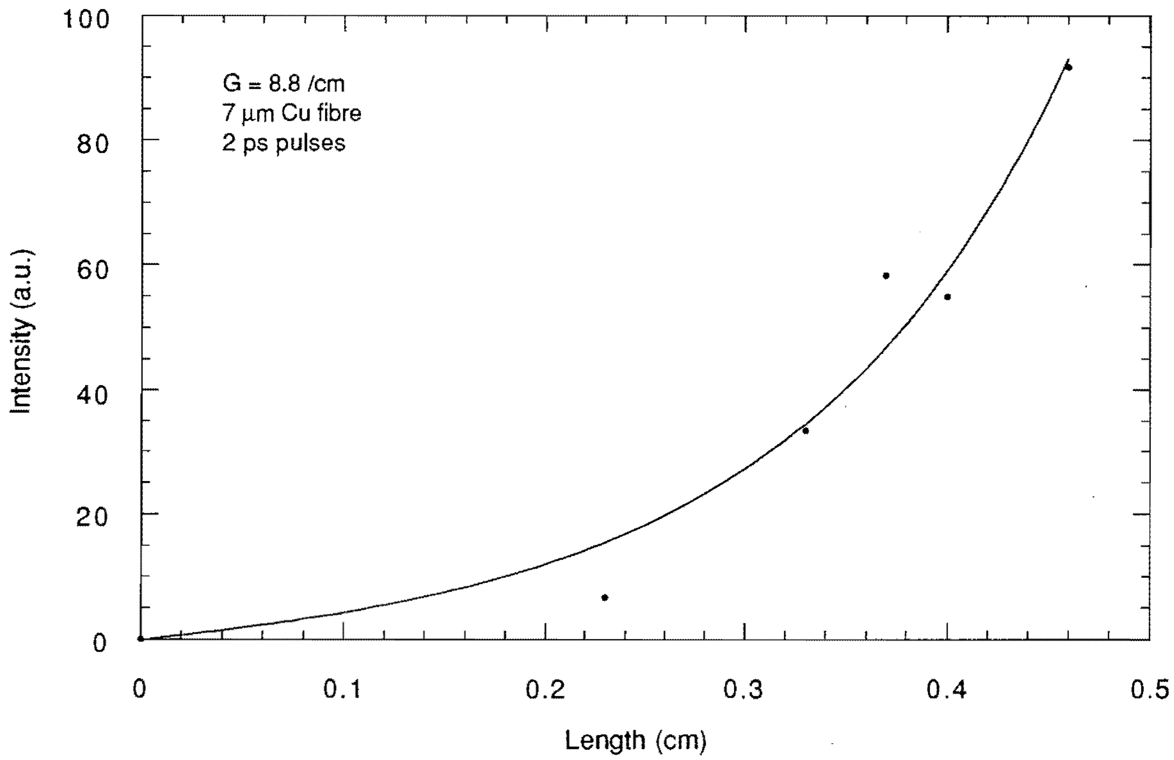



Figure 7. The fitted gain to the data from figure 4 for the 5g - 4f transition in sodium-like copper ions using Linford formula.

## (ii) Comparison of Plasma Emission Generated by ns and ps Pulses

The pulses, with a maximum energy of 45 J, were focused by means of an off-axis parabola in conjunction with an off-axis spherical mirror to a line 6 - 7 mm long and 20 μm wide. Thus, for a 1 ns and a 2 ps pulse, after a 50% reflection loss by the compression gratings and focusing system, intensities up to $1 \times 10^{13}$ and $5 \times 10^{15}$ W/cm$^2$, respectively, were reached in the focal region. Fibre targets with a diameter of 7 μm were irradiated, thus, only about one third of the laser energy reached the target. The fibres were supported on one end and positioned with better than ±2 μm spatial accuracy and ±1 mrad angular accuracy by using a modified split-field microscope system [4]. The targets were fabricated by coating carbon fibres [12], 7 μm in diameter, with a thickness > 300 Å NaF, Al, Cu or Fe layer. It turned out that the deposition process frequently resulted in bending of the fibre targets. Only fibres with a deviation from straightness of less than 20 μm were used in the experiment.

To record the soft x-ray spectra, a flat-field spectrometer [4] coupled to a x-ray sensitive fluorescent-screen CCD camera was installed axially to the fibre target. For a number of shots Shanghai x-ray film (SIOFM-5FW) or Kodak 101-05 plates were used as the detector, in which case the evaluation of the spectra was carried out by means of a digital densitometer. The densitometer yielded time-integrated spectra with a spectral resolution of about 0.2 Å and with a spatial resolution better than 40 μm. The data were Abel-inverted along the spatial co-ordinate to take the cylindrical symmetry of the experiment into account.

In figs. 8 - 10 spectra of NaF, Al and Cu plasmas generated with 1 ns and 2 ps pulses are shown. The pulse energies and the lengths of fibre are indicated on the spectra. These spectra are integrated over a spatial region with r > 50 μm (here r represents the radial distance from the fibre surface). It is quite conspicuous that in all cases the ps spectra show a significantly higher ratio of continuum to line intensity. This can be attributed to a number of reasons related to opacity, line broadening effects etc.

The spectra allow comparison of the ionisation stages generated with the different pulse durations. In NaF the ns and ps spectra show that essentially the same ionisation stages are reached. Li-like Na and Li-like F lines predominate. H-like and He-like F can also be seen, while He-like and H-like Na lines are absent.

For aluminium the situation is quite different: While the spectra with ns pulses show a predominance of Li-like recombination lines (in particular the gain lines 3d-4f and 3d-5f at 154 and 106 Å the spectra with 2 ps pulse duration are dominated by lines emitted from relatively low ionisation stages, with Ne-like, F-like and O-like lines being the most prominent ones. The Li-like 3d-4f line appears

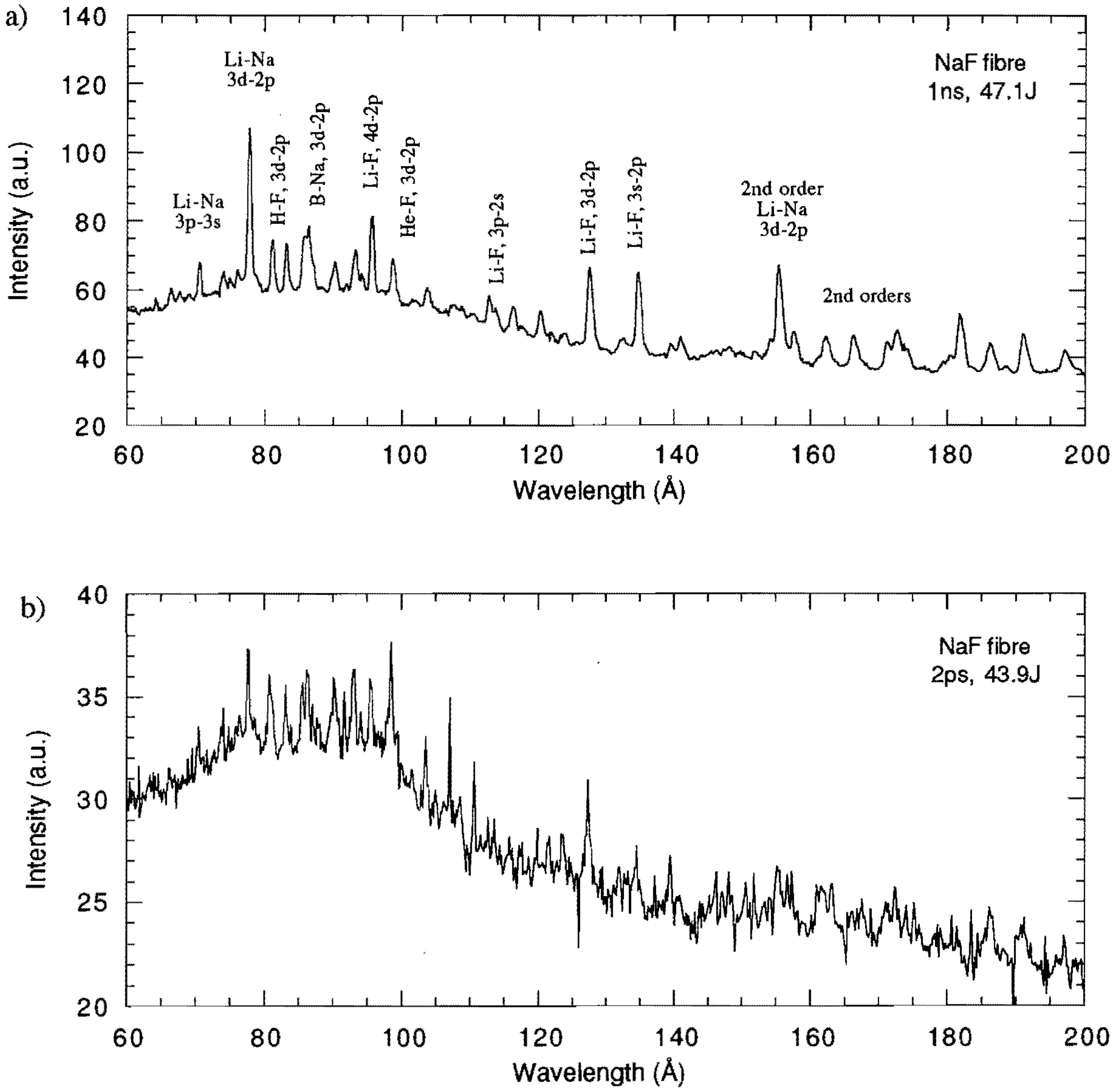
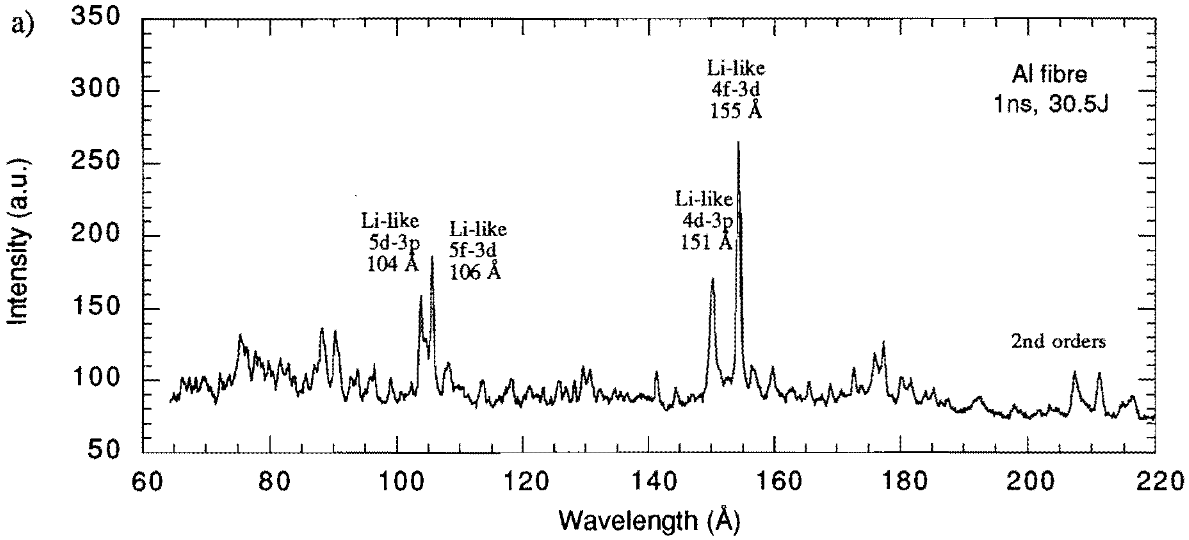



Figure 8  Axial spectra of 7 μm diameter carbon fibres coated with 3000 Å of NaF.
a) 1 ns duration,  b) 2 ps duration.



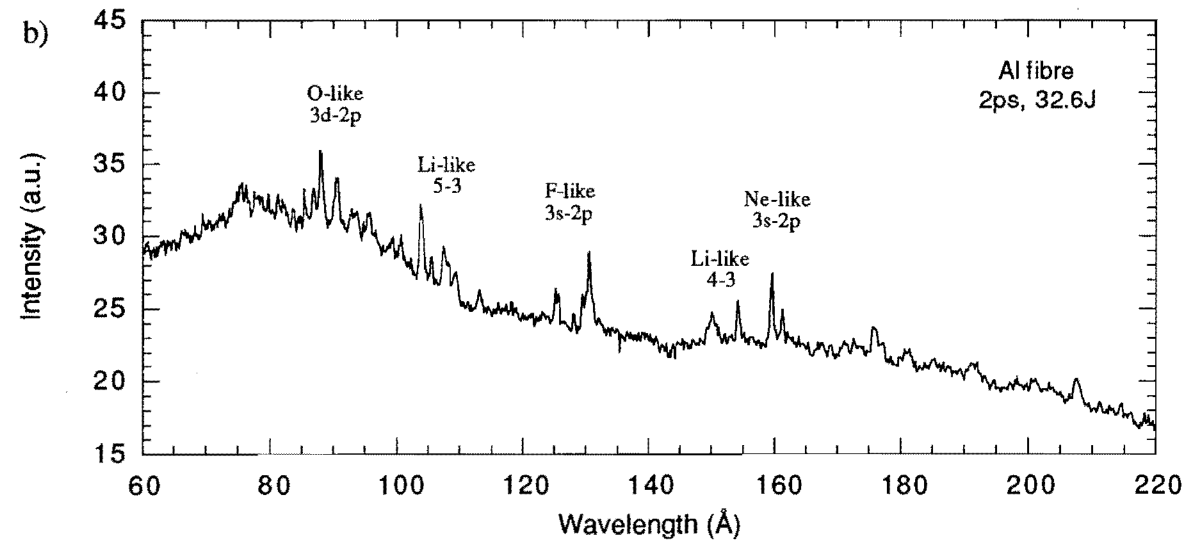




Figure 9. Axial spectra of 7 μm diameter carbon fibres coated with 3000 Å of Al.
a) 1 ns duration. b) 2 ps duration.

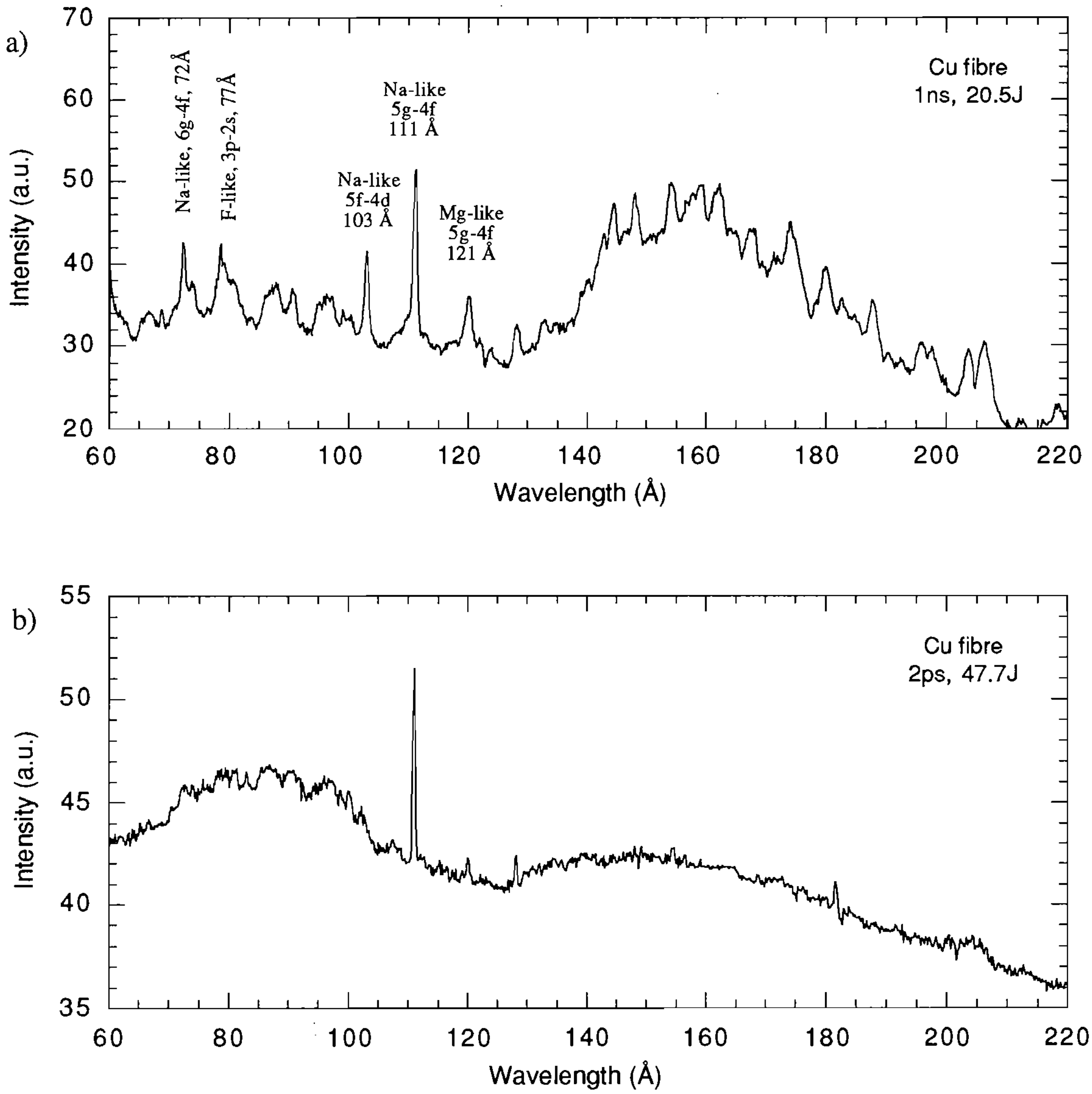



Figure 10. Axial spectra of 7 μm diameter carbon fibres coated with 3000 Å of Cu.
a) 1 ns duration. b) 2 ps duration.

The spatial extent of the emission was quite different for the two pulse durations. For ns pulses the time-integrated spatially resolved spectra show a typical fall-off of the line emission within a region of 300 μm, whereas for the ps pulses the emission terminates much closer to the target, typically around 100 μm from the target surface. This observation is explained by the simulations to be due to the sharp density gradients and the rapid decay of the density perpendicular to the target surface for ps pulses.

The anomalously strong emission on the 5g-4f line in Na-like Cu and Fe ions suggests that there is gain on that recombination line. This is accord with the simulation results, which predicts a gain coefficient of about 10 $cm^{-1}$ under the conditions of the experiment.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] J Zhang, M H Key, S J Rose, and G J Tallents, Phys. Rev. A**49**, 4024 (1994).
[2] J Zhang, M H Key, J. Appl. Phys. **74**, 7606 (1993).
[3] J Zhang and M H Key, Appl. Phys. B**58**, 13 (1994).
[4] J Zhang, M H Key et al, Phys. Rev. Lett. **74**, 1335 (1995).
[5] P Jaegle, G Jamelot, et al, J. Opt. Soc. Am. B**4**, 563 (1987).
[6] Steingruber and E E Fill, Appl. Phys. B**58**, 29 (1994).
[7] C E Max, "Physics of the coronal plasma in laser fusion targets", in *Laser Plasma Interactions*, eds. R. Balian and J C Adam, Amsterdam, The Netherlands: North Holland, 1982.
[8] See papers in *X-rays from Laser Plasmas*, ed. M C Richardson, SPIE, Bellingham, WA, Vol. 831, 1988.
[9] P Maine et al., SPIE Vol. 913 (1988) 140.
[10] C N Danson et al, Opt. Commun., **103**, 392 (1993).
[11] J Zhang, *Annual Report 1995* (1995).
[12] Supplied by Sigri Great Lakes Carbon GmbH, D-86405, Meitingen, Germany.