R-LINE MEASUREMENTS USING SMALL RUBY SENSORS IN IMPACT EXPERIMENTS.

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I INTRODUCTION

In this report, we summarize the experimental details and results from our ruby experiments carried out in projects 188 and 196. The primary function of this report is the compilation of experimental details and results for use in subsequent project reports and / or papers. As such, it is designed to be a working document for individuals working on this project. The information presented here is important in using the ruby sensor as a stress gauge in a variety of shock wave experiments.

II CALCULATION OF THE STRESS IN THE TARGETS

In each experiment we quote a value for the stress in the target. This value has been derived from knowledge of the flyer plate and target materials and an experimentally determined value for the impact velocity. We have carried out a graphical impedance matching calculation to obtain each value. Below we list the Hugoniot curve we have used for each material. We have also listed Hugoniot data for materials that we intend to use in the future. The longitudinal stress, σ, is expressed in kbar and the particle velocity, u_p, in km s^{-1}.

Table 1

Material	Hugoniot
Al 60-61	$\sigma = 34.1294u_p^2 + 152\cdot468u_p - 4.11313$
Copper	$\sigma = 125.71u_p^2 + 376.453u_p - 13.7594$
Carrara Marble	$\sigma = -6165.85u_p^4 + 6091.5u_p^3 - 2049.72u_p^2 + 372.704u_p - 6.64083$
Steel 304	$\sigma = 114.943u_p^2 + 367.399u_p - 2.32594$
PMMA	$\sigma = 20.0908u_p^2 + 27.3101u_p + 0.882401$
Fused silica	$\sigma = -8.83527u_p^2 + 119.871u_p + 0.286328$

The graphs on the following pages (Figures 1- 6) depict the available Hugoniot data on these materials. The points represent experimental measurements; the curves represent our curve-fit. The functional form of each fit is shown in Table 1.
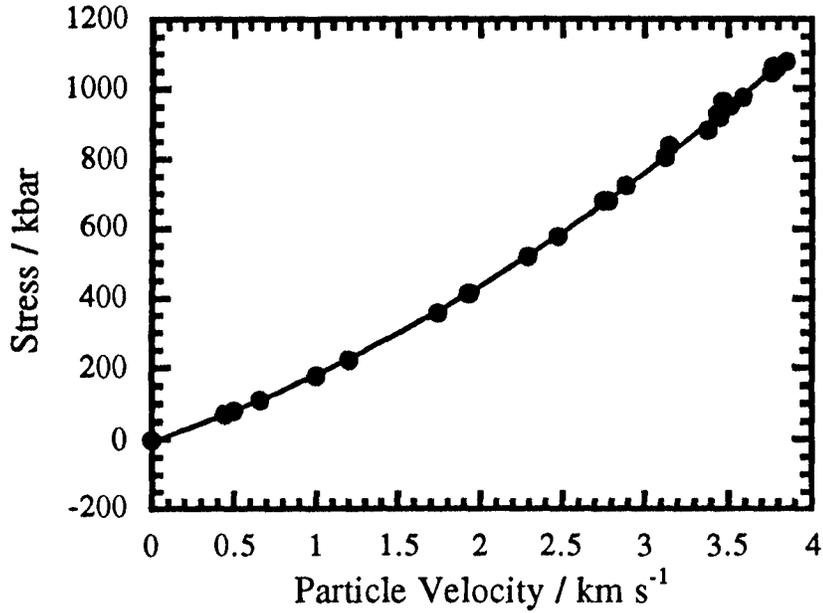
Figure 1

Hugoniot Curve for Aluminum 6061. The points represent the experimental measurements obtained from LASL Shock Hugoniot Data (S. P. Marsh, ed., Univ. of California Press, 1980). The curve represents our curve-fit.

Figure 2

Hugoniot Curve for Copper. The points represent the experimental measurements obtained from LASL Shock Hugoniot Data (S. P. Marsh, ed., Univ. of California Press, 1980). The curve represents our curve-fit.
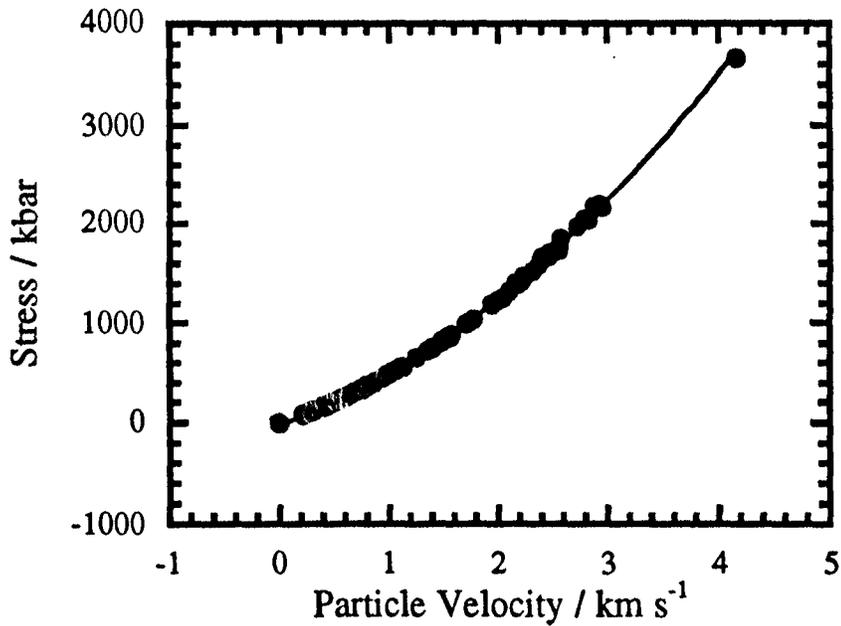
Figure 3

Hugoniot Curve for Carrara Marble. The points represent the experimental measurements obtained from J. Aidun's thesis. The curve represents our curve-fit.

Figure 4

Hugoniot Curve for Steel 304. The points represent the experimental measurements obtained from LASL Shock Hugoniot Data (S. P. Marsh, ed., Univ. of California Press, 1980). The curve represents our curve-fit.
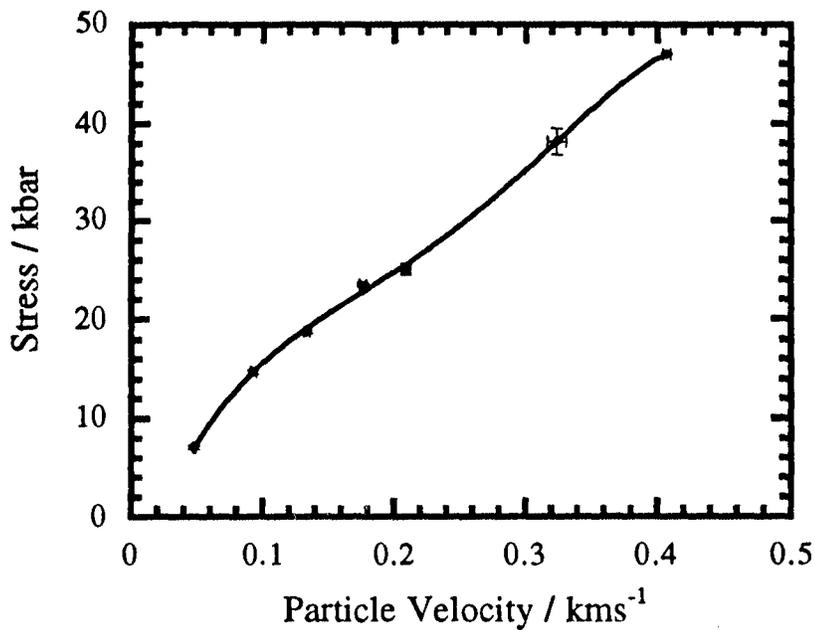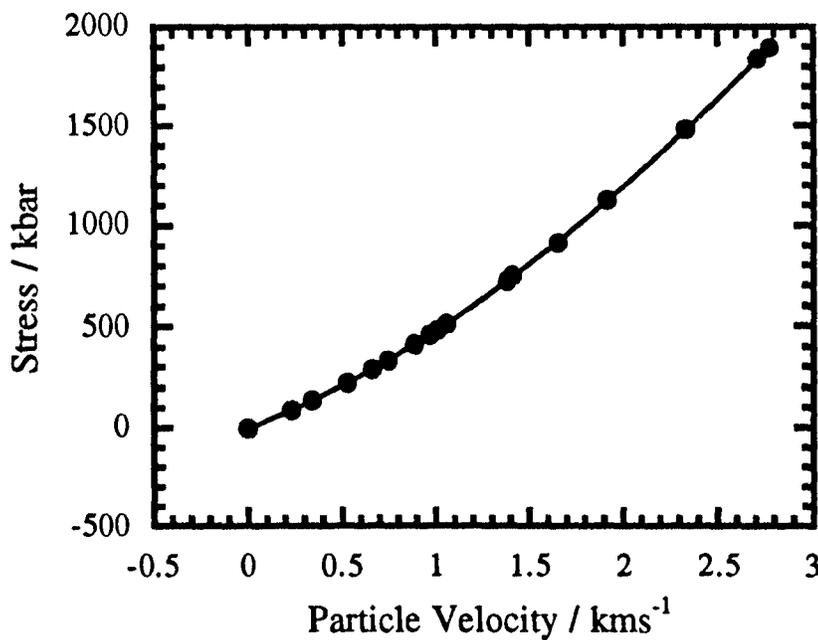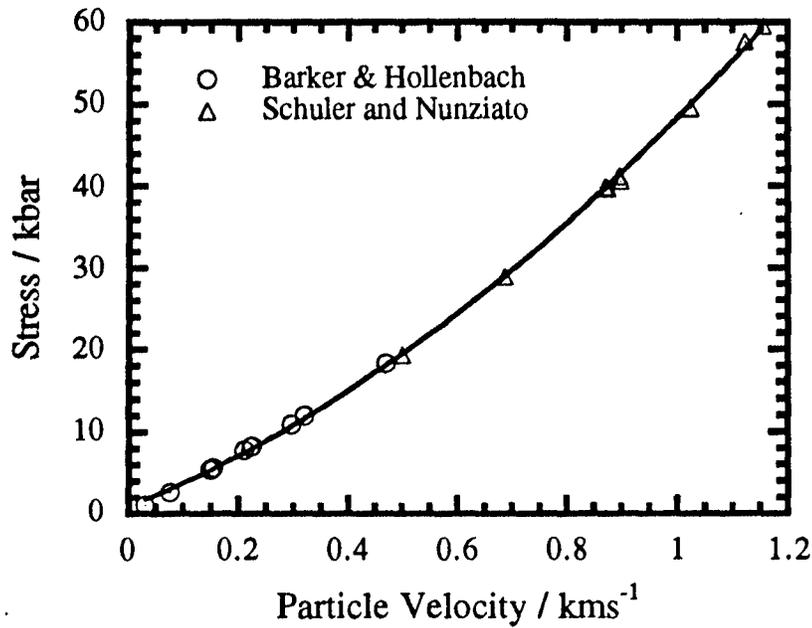
Figure 5

Hugoniot Curve for PMMA. The points represent the experimental measurements obtained
from Barker and Hollenbach (J. Appl. Phys. **41**, 4208, 1970) and Shuler and Nunziato
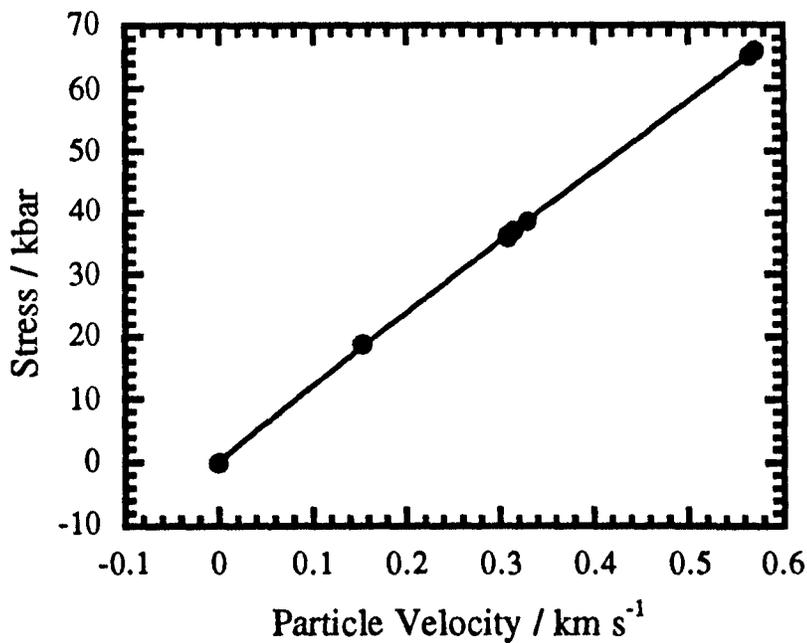(Rheol. Acta **13**, 265, 1974). The curve represents our curve-fit.

Figure 6

Hugoniot Curve for fused silica. The points represent the experimental measurements
obtained from Barker and Hollenbach (J. Appl. Phys. **41**, 4208, 1970). The curve
represents our curve-fit.

We will now present in detail the method of calculation of the stress values presented in this work. We assume the following impact configuration with materials 1 and 2 used for the impactor and matrix, respectively.
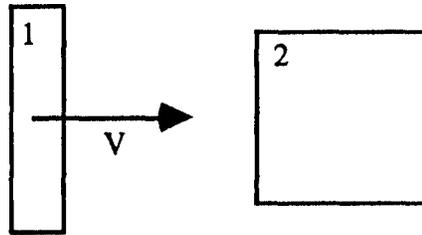

Figure 7

We assume material 1 as the impactor and 2 as the target.

To obtain values of the final stress (σ_F) and particle velocity (u_F), we make use of the already known Hugoniot data for the two materials. The following plot shows the graphical solution.
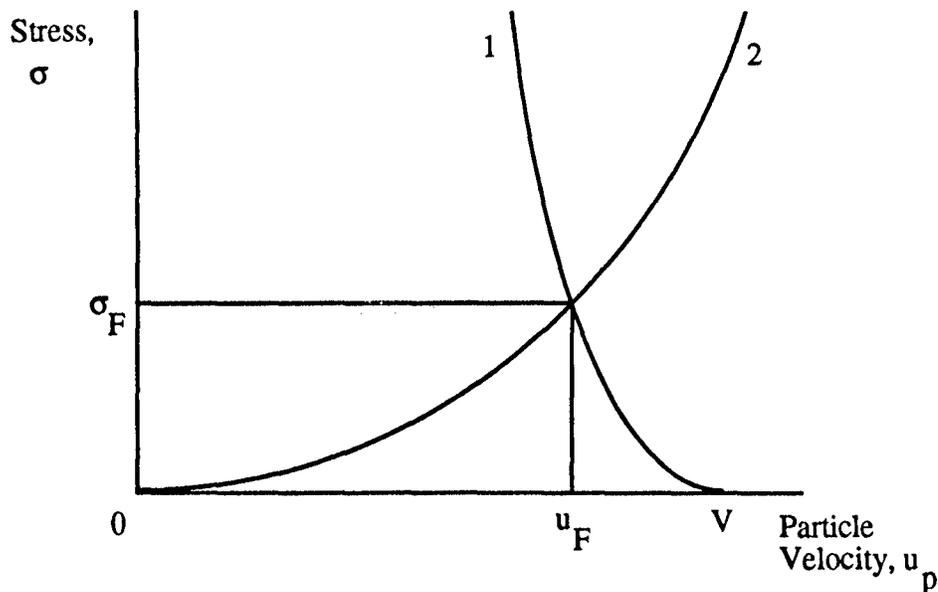

Figure 8

Graphical impedance matching calculation of the peak stress arising from the arrangement in Figure 7.

To obtain an analytical solution we assume curve-fits to the available Hugoniot data, as follows:

Hugoniot for material 1:

$$\sigma_1 = au_p^2 + bu_p + c = H_1(u_p)$$

Hugoniot for material 2:

$$\sigma_2 = du_p^2 + eu_p + f = H_2(u_p)$$

$$\Rightarrow \quad \sigma_F = du_F^2 + eu_F + f = a(V - u_F)^2 + b(V - u_F) + c$$

$$= aV^2 + au_F^2 - 2aVu_F + bV - bu_F + c$$

$$\Rightarrow \quad (a - d)u_F^2 + (-b - e - 2aV)u_F + (c + aV^2 + bV - f) = 0$$

The solutions for the final stress and particle velocity values are:

$$\Rightarrow \quad u_F = \frac{(b + e + 2aV) \pm \sqrt{(b + e + 2aV)^2 - 4(a - d)(c + aV^2 + bV - f)}}{2(a - d)}$$

$$\sigma_F = H_1(V - u_F) = H_2(u_F)$$

In the calculations carried out in this work, we have used the following curve fits to the Hugoniot data:

Al (60-61 T6): $\quad \sigma = 34.1294u_p^2 + 152 \cdot 468u_p - 4.11313$

Cu (OFHC): $\quad \sigma = 125.71u_p^2 + 376.453u_p - 13.7594$

For symmetric impact, the solution becomes:

$$u_F = \frac{V}{2}, \quad \sigma_F = H\left(\frac{V}{2}\right)$$

where H denotes the Hugoniot function.

For asymmetric impact, the solutions for the particle velocity are:

(i) Cu impactor, Al target:

$$u_F = \frac{(528.921 + 251.42V)}{183.1612} \pm \sqrt{\frac{(528.921 + 251.42V)^2}{33548.03} - \frac{(125.71V^2 + 376.453V - 9.64627)}{91.5806}}$$

(ii) Al impactor, Cu target:

$$u_F = \frac{(-528.921 - 68.2588V)}{183.1612} \pm \sqrt{\frac{(528.921 + 68.2588V)^2}{33548.03} - \frac{(34.1294V^2 + 152.468V + 9.64627)}{91.5806}}$$

Values for the final stress were obtained from u_F by making use of the target Hugoniot function.

III EXPERIMENTAL METHOD AND RESULTS

The appendices give the experimental configuration, the raw data and the variation in peak positions, R-line splitting and peak intensities as a function of time for each experiment. Table 2 summarizes various configurations and derived parameters. We will treat each section of Table 2 separately. Each of the following subsections also corresponds to a separate Appendix. The experiments are numbered by their appendix letter followed by a number that increases consecutively according to the type and the date of the experiment.

In our experiments we used Aluminum 6061 and OFHC grade Copper.

1. Diagnostic experiments

We have carried out two experiments (A1 (93544) and A2 (93545)) using our traditional ruby disk arrangement with sapphire backing. The purpose of these experiments was to determine which of the two adhesives (Norland Optical Adhesive No. 68 or the 815 epoxy) was more suitable for our experiments. The former adhesive is more convenient to use because it can be partially cured by exposing for 10 minutes to UV light, after which time the quality of the bond and the cleanliness of the interface can be easily checked prior to full curing in an oven. These two experiments have shown a 30 % decrease in the signal intensity upon shock arrival at the ruby. This intensity change is fully recovered upon arrival of unloading waves at the ruby. There is no difference in signal quality between the two experiments. Consequently it appears that the two adhesives can be used interchangeably. It is not clear why we observe the intensity decrease during shock compression.

2. Preliminary Experiments

The first two of these experiments (B1 (93508) and B2 (93510)) involved lens coupling of the fiber to the sample. The latter was a piece of ruby that was placed in a hole drilled in an aluminum sheet of the same thickness. The whole sheet was bonded to a sapphire back plate. Following minor refinements in the target preparation, spectra of reasonably good quality were obtained in B2. Although the target configuration will not be of great use in the long run, this set of experiments was useful in demonstrating that it is possible to excite and collect luminescence spectra from ruby disks of such small dimensions (1mm diameter x 0.25 mm thickness).

Experiments B3 (93-515) and B4 (93-518) represent our initial attempts at the current target configuration. The first experiment was encouraging: Although there is a decrease in intensity of around 50% upon arrival of the shock wave at the ruby, both R-lines are clearly discernible until the first unloading wave comes in. B4 (69 kbar) however gave a large background increase at impact and very poor subsequent spectra. This indicates a problem with the ruby chip and/or with the ruby-fiber interface. The ruby chips up to this point were being cut in this laboratory and were of significantly lower quality than the ones used in subsequent experiments. This is one possible source of irreproducibility in our results.

There is one other experiment in which we used one of these 1 mm diameter ruby chips: the rod impact experiment D1 (93519: 131 kbar, Cu target and impactor). Again in this experiment, the luminescence signal is lost as soon as the shock arrives at the ruby. We now know that the fused silica fiber does not survive at such high stresses and that the

matching of its shock impedance to that of the matrix material has a strong influence on the recording time.

From among these five experiments only B2 (93510), B3 (93515) and perhaps B4 (93518) merit further analysis. B3 and B4 will be mentioned again in subsequent sections.

3. Uniaxial Strain Experiments

We will discuss the uniaxial strain experiments in aluminum and copper matrices separately.

a. Aluminum Targets

There are six experiments that are worth discussing: B3 (93515: 54 kbar), C1 (93522: 55 kbar), C2 (93528: 56 kbar), C5 (93530: 67 kbar), C6 (93536: 79 kbar), and C7 (93537: 100 kbar). In all these experiments the recording time (which is determined by the transmission characteristic of the fiber) is satisfactory. We always observe at least some luminescence signal during compression and subsequent release of the ruby sample. However, the intensity of the luminescence during compression and the general quality of the signal seem to decrease consistently with stress. 70-80 kbar seems to represent the transition between acceptable and unsatisfactory signals with the fused silica fiber. There does not seem to be a significant difference in performance between the UV and NIR fused silica fibers.
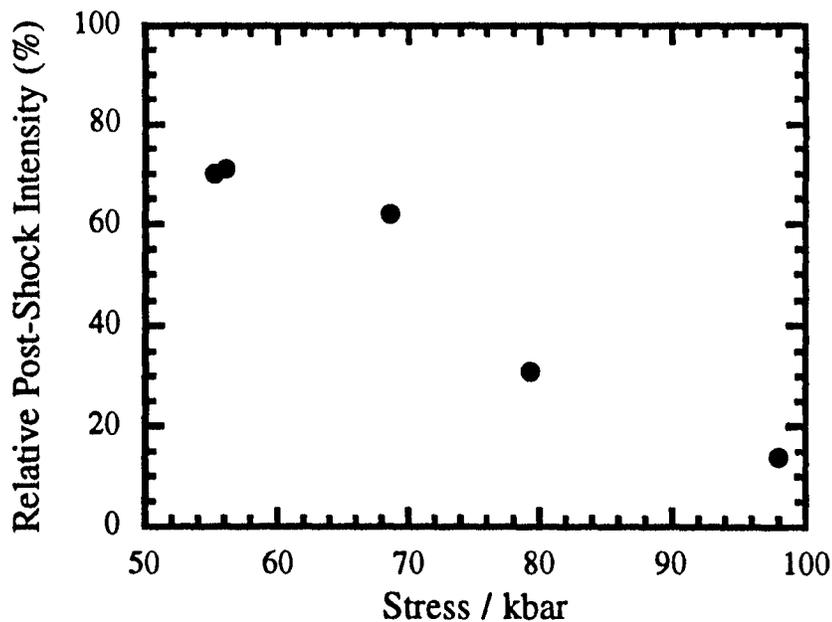

Figure 9

A plot of the relative post-shock intensity of the luminescence against stress in an Aluminum matrix.

Figure 9 shows an empirical plot of relative post-compression intensities of the luminescence signal as a function of stress in an Aluminum target. Only the experiments listed under uniaxial strain in Table 2 are represented. The values on the abscissa were obtained by comparing the peak intensities in the first clear track after shock arrival at the ruby with the signal intensities prior to impact. The discontinuity between 70 and 80 kbar is thought to arise from inelastic changes in the fused silica fiber and represents the limit of usefulness of this fiber.

The highest value achieved for post-compression intensities is 70% (C1 (93522) and C2 (93528)). This figure is identical to the one observed in standard ruby disk / sapphire backing shots (A1 and A2), albeit at much higher stresses, with the UV cured and 815 epoxies, respectively. The latter two experiments have shown that the two kinds of epoxy can be used interchangeably. It is interesting to note that in experiments A1 (93544), A2 (93545), C2 (93528), C5 (93530) and D2 (93529) there is complete recovery in the peak intensities upon arrival of unloading waves at the ruby. Even experiments C6 (93536) and C7 (93537), in which the effects of an inelastic deformation in the fused silica fiber seem to be observable, show some recovery in the signal intensity upon unloading.

All six experiments mentioned at the beginning of this subsection merit further analysis.
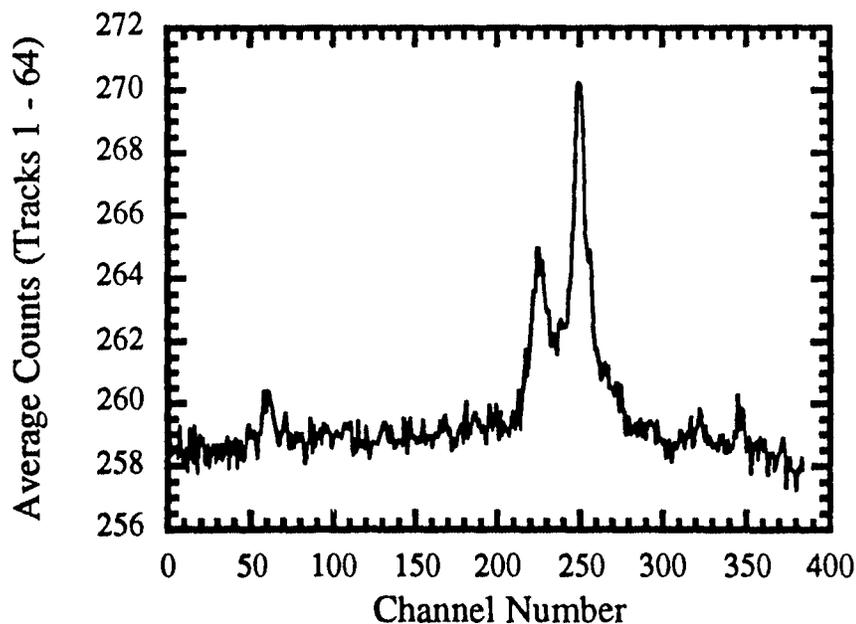

Figure 10

Luminescence signal from impurity in SAPHICON sapphire fiber. The fiber was 400 μm in diameter, 2" long and was received already polished.

<u>b. Copper Targets</u>

We have carried out three uniaxial strain experiments in a copper matrix. C8 (93532: 68 kbar) involved a fused silica fiber. This experiment gave good quality spectra but with a shorter transmission time (2.3 μs) and a lower post-shock intensity than the corresponding experiment in aluminum (C5: 93530: 6 μs, 62%). It would appear that the shock impedance matching between the fiber and the matrix material has a strong influence on the total transmission time. It is still possible that at lower stresses we can obtain satisfactory recording times with the fused silica fiber in copper.

Experiments C3 (93535: 121 kbar) and C4 (93539: 87 kbar) represent our first two attempts with sapphire fiber. In the first shot, the fiber was polished in this laboratory and the quality of the target was consequently problematic. In this experiment, we lose all the signal at the moment the shock arrives at the ruby. The only signal observed after this time is due to the chromium impurity in the fiber and appears to be low enough to make the fiber potentially useful (see also Figure 10). Experiment C4 (93539) involved a sapphire fiber polished by SAPHICON. The post shock intensity of the signal is low (30%) and the recording time is only 1.4 μs. However, the two R-lines are clearly discernible throughout this time.

The last two experiments should be treated as preliminary shots on the sapphire fiber. Experiments C4 (93539) and C8 (93532) have given data that are worthy of further analysis.

<u>4. Rod-Impact Experiments</u>

These experiments are designed to demonstrate potential application of the ruby sensor to the penetration problem. Three experiments have been carried out, all of which employed a fused silica fiber.

Two of these were in copper targets (D1: 93519, 131 kbar; D3: 93531, 68 kbar). These experiments gave low post-shock intensities (26% and 30% respectively) and poor transmission durations (1 μs and 1.5 μs, respectively). The spectra are poor in quality and consequently neither of these two experiments deserves further analysis.

The remaining experiment was in an aluminum matrix (D2: 93529, 67 kbar). The post-shock intensity was adequate (50%) to give spectra of reasonable quality and the recording time was excellent (6 μs). The signal intensity appears to recover upon unloading of the sample and to remain above 80% of the original intensity during the complicated loading path that follows. This experiment deserves careful examination and could potentially have implications on our understanding of the penetration problem.

5. Preliminary Analysis

In Figure 11, we plot the observed initial compression shift in the ruby R1-line as a function of stress for all the experiments that employed the current configuration. The line of slope 0.365 Å/kbar is also shown, for comparison. Under hydrostatic conditions, both lines are known to shift towards longer wavelengths at approximately this rate (D. M. Adams et al. J. Phys. E, **9**, 1140, 1976). Figure 12 shows the equivalent plot of the initial shift in the R2 line.
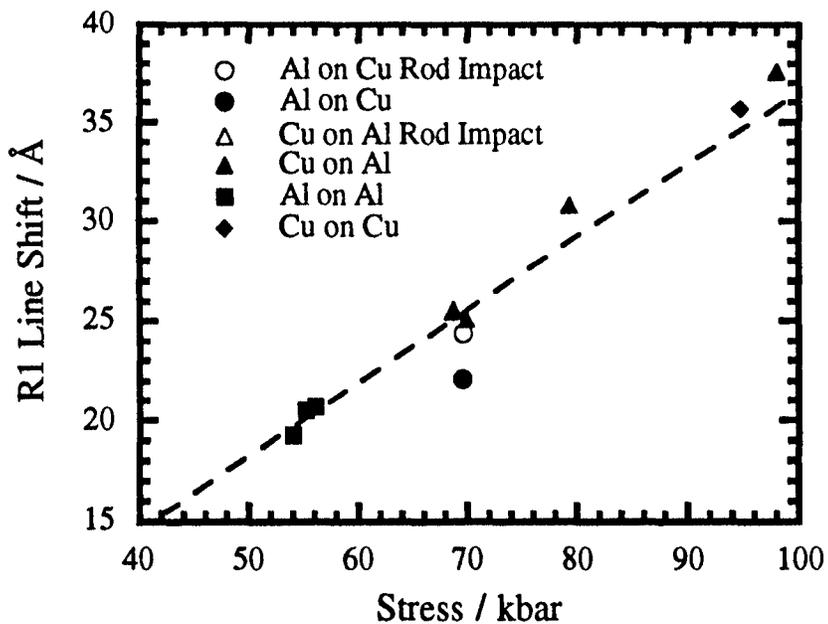

Figure 11

Shift in R1 Line as a function of stress for all the shots that employed the current target configuration. The dotted line has a slope of 0.365 Å/kbar and represents the shift under hydrostatic conditions..
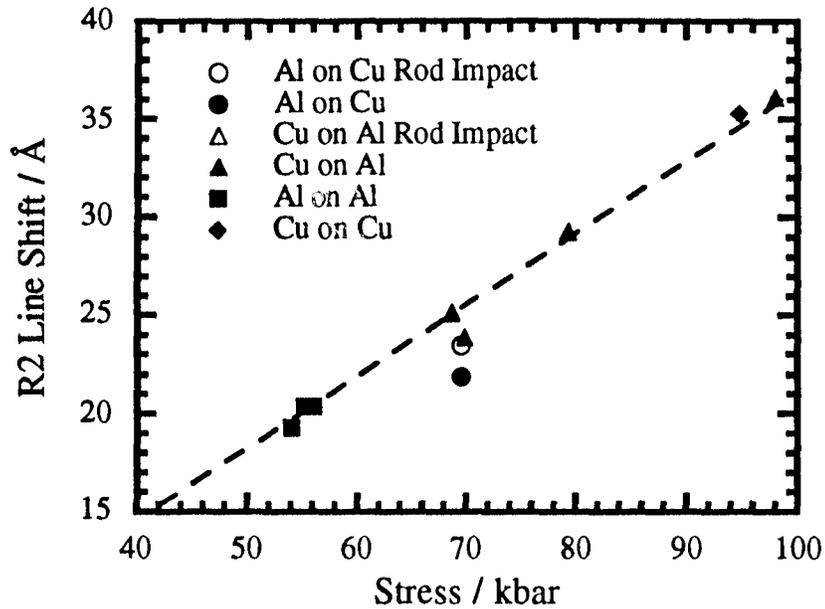
Figure 12

Shift in R2 Line as a function of stress for all the shots that employed the current target configuration. The dotted line has a slope of 0.365 Å/kbar and represents the shift under hydrostatic conditions.

Experiments C5 (93530) and C8 (93532) were carried out at roughly the same stress (67 kbar) in aluminum and copper respectively. The measurements gave reasonably good quality spectra for long enough time durations to merit comparison (Figures 13 and 14). The data from experiment B4 (93518) are not as good in quality but they are included in Figures 13 and 14. This comparison also serves as a preliminary attempt at further analysis of the data.

Figure 13 - R-Line Shifts at 70 kbar

Figure 14 - R- Line Splitting at 70 kbar

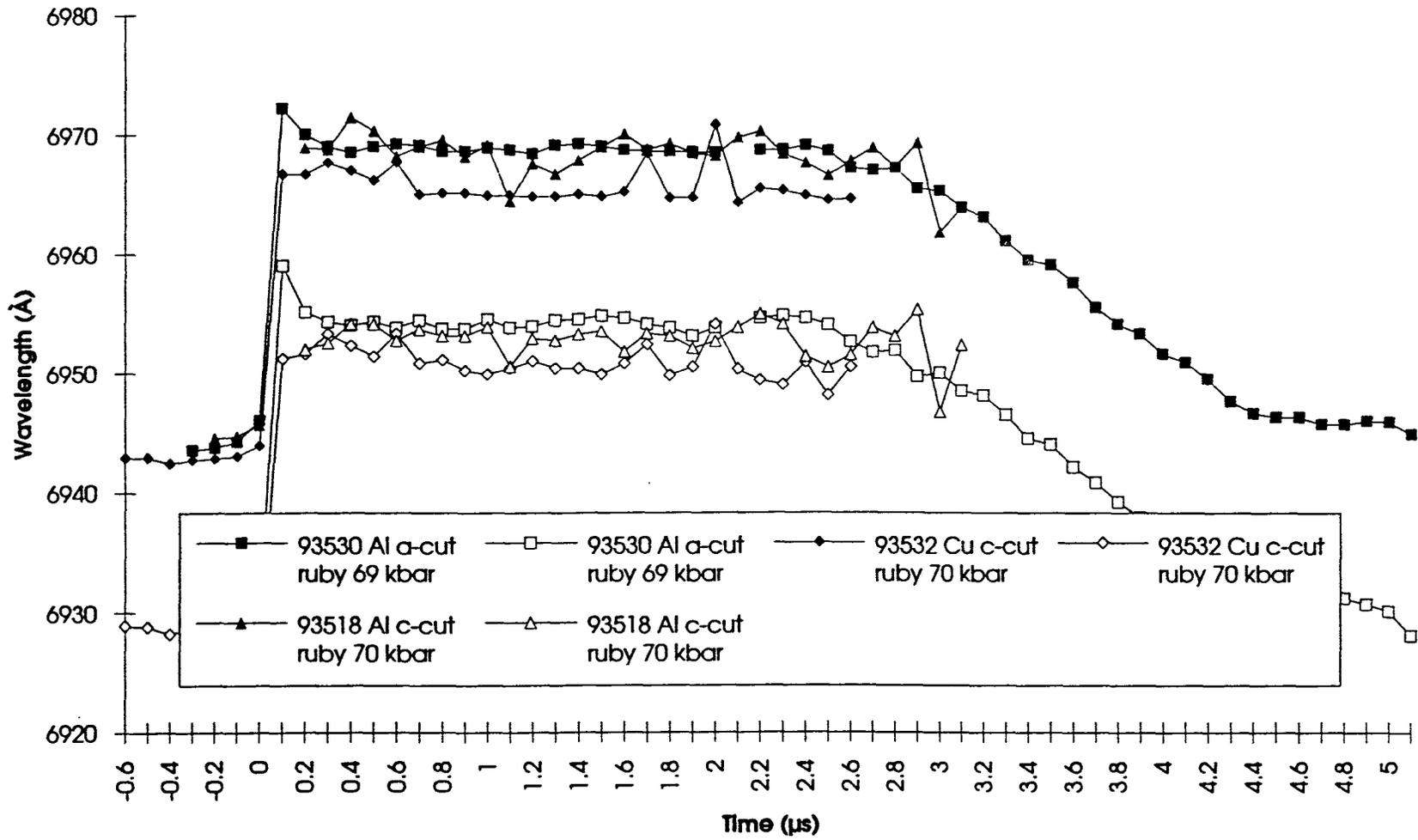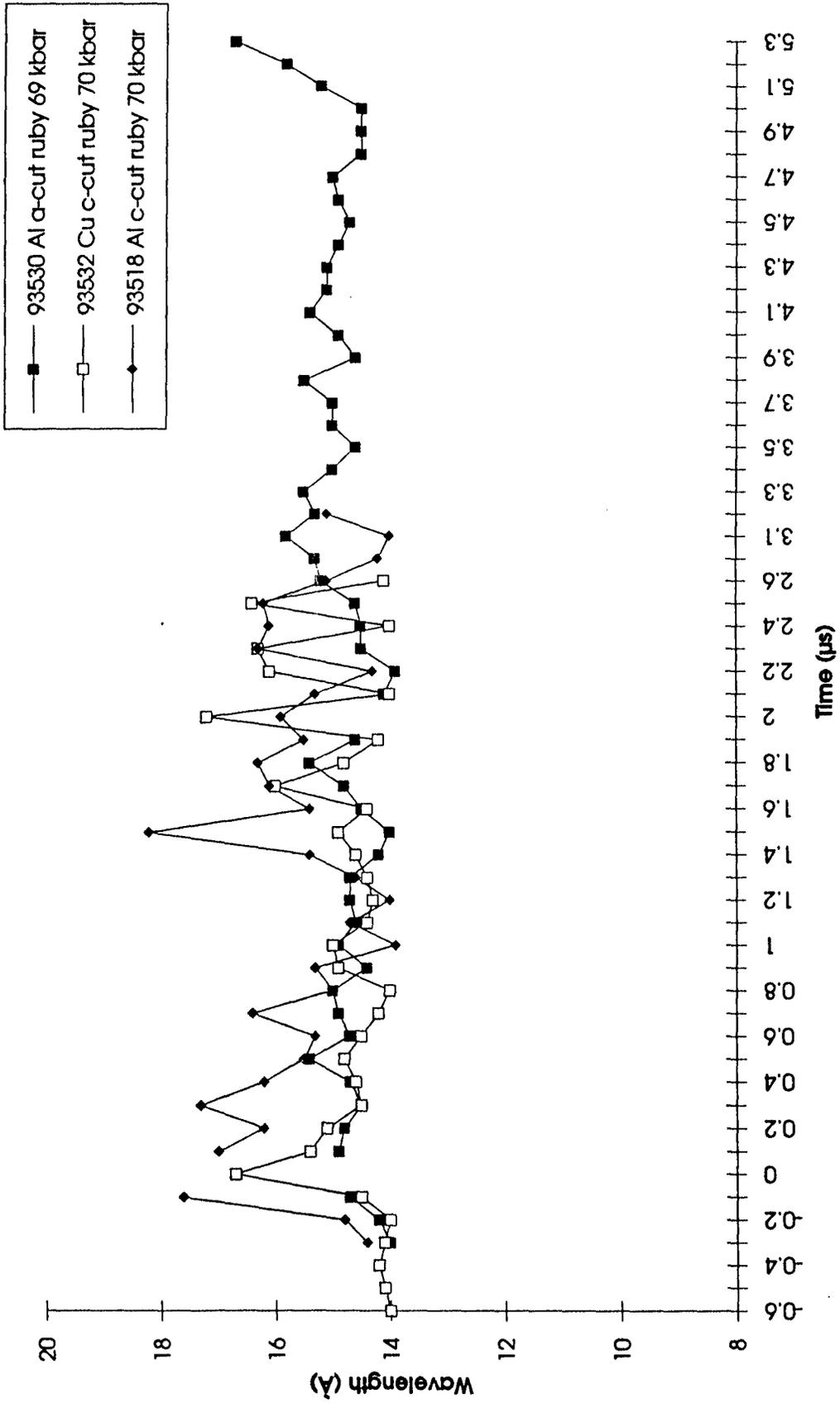| Experiment #	Impactor - Target Material	Proj. vel. (mm/µs)	Stress (kbar)	R1 Shift (Å)	R2 Shift (Å)	Average Splitting	Broadening R1 (Å)	Broadening R2 (Å)	Ruby Orientation	Ruby Specs diam. x depth (mm)	Target Dimensions (diam. x thick) (mm)	Impactor Dimensions (diam. x thick) (mm)	Buffer Dimensions (diam. x thick) (mm)
Diagnostic Experiments													
A1 (93544)	Sapphire-Ruby	0.544	120	22.8	25.2	-2.4	no	no	c	19.1 x 0.250	ruby backed by sapphire	25.4 x 1.59	na
A2 (93545)	Sapphire-Ruby	0.539	120	23.3	26.3	-3.0	no	no	c	19.1 x 0.250	ruby backed by sapphire	25.4 x 1.59	na
Preliminary Experiments													
B1 (93508)	*Al - Al	0.707	54.1	31.5 ne	31 ne	no	no	no	c	1.000 x 0.250	31.7 x 0.250	22.2 x 15.2	na
B2 (93510)	*Al - Al	0.704	53.8	30 ne	31.7 ne	1.7±0.5	no	no	c	1.000 x 0.250	31.7 x 0.250	22.2 x 15.2	na
B3 (93515)	Al - Al	0.701	53.5	19.3 ne	19.3 ne	0	no	no	c	1.000 x 0.250	38.1 x 19.1	63.5 x 12.7	38.1 x 3.18 np
B4 (93518)	Cu - Al	0.640	68.7	25.1 ne	23.9 ne	1.2±0.7	na (ps)	na (ps)	c	1.000 x 0.250	38.1 x 19.1	44.5 x 18.4	na
Rod Impactor Experiments													
D1 (93519)	Cu - Cu	0.691	131.1	40 ne	40 ne	0	no (ps)	no (ps)	c	1.000 x 0.250	38.1 x 19.1	12.7 x 50.8	38.1 x 2.92 np
D2 (93529)	Cu - Al	0.629	67.3	25.6 e	25.2 e	0	0.5±0.4	0.5±0.5	c	0.500 x 0.250	38.1 x 19.1	12.7 x 50.8	38.1 x 1.50 p
D3 (93531)	Al - Cu	0.631	67.5	24.4 ne	23.5 ne	0.8±0.4	2.5±0.7	1.9±1.2	c	0.500 x 0.250	38.1 x 19.1	12.7 x 50.8	38.1 x 1.50 p

General Comments:

* = Lens coupling, thin aluminum sample   ps = Poor Spectra   no = not observed

e = Elastic Precursor observed   p = Polished buffer plate

ne = Elastic precursor not observed   np = buffer plate Not Polished

Table I

Relative Post Impact Intensity	Record Time (µs)	Fiber Type	Method of Stripping	Glue Used	Background Increase	Comments

Diagnostic Experiments

Relative Post Impact Intensity	Record Time (µs)	Fiber Type	Method of Stripping	Glue Used	Background Increase	Comments
71% / 71%	1.15	na	na	Norland 61	no	This and the next shot were performed to test the relative effect of the two different epoxies used and to determine if the intensity drop seen in the
71% / 73%	0.68	na	na	Epon 815	no	chip experiments was seen in the normal disc experiments. There was no difference between the epoxies and there was a decrease in intensity.

Preliminary Experiments

Relative Post Impact Intensity	Record Time (µs)	Fiber Type	Method of Stripping	Glue Used	Background Increase	Comments
27%	~1.40	lens coupled	na	Epon 815	none observed	1mm ruby chip embedded in Al disc glued on a sapphire backing, spectra not excellent
56%	~1.80	lens coupled	na	Epon 815	none observed	same configuration as in B1, spectra not bad
50%	~3.80	UV fused Silica	mechanical	Epon 815	~2.6 µs	Good spectra
22%	~3.00	UV fused Silica	mechanical	Epon 815	~3.3 µs	The spectra are poor from impact on, values listed are from only three good tracks

Rod Impactor Experiments

Relative Post Impact Intensity	Record Time (µs)	Fiber Type	Method of Stripping	Glue Used	Background Increase	Comments
26%	~1.00	UV fused Silica	Chemical	Epon 815	300ns slight	The spectra are poor from impact on, values listed are from track 7 only
50%	6.00	NIR fused Silica	Chemical	Norland 68	none observed	
30%	~1.50	NIR fused Silica	mechanical	Norland 68	none observed	Spectra are poor, data taken from tracks 5, 6, 7, & 8

Table II

Experiment #	Impactor - Target Material	Proj. vel. (mm/μs)	Stress (kbar)	R1 Shift (Å)	R2 Shift (Å)	Average Splitting	Broadening R1 (Å)	Broadening R2 (Å)	Ruby Orientation	Ruby Specs diam. x depth (mm)	Target Dimensions (diam. x thick) (mm)	Impactor Dimensions (diam. x thick) (mm)	Buffer Dimensions (diam. x thick) (mm)

Uniaxial Strain Experiements

Experiment #	Impactor - Target Material	Proj. vel. (mm/μs)	Stress (kbar)	R1 Shift (Å)	R2 Shift (Å)	Average Splitting	Broadening R1 (Å)	Broadening R2 (Å)	Ruby Orientation	Ruby Specs diam. x depth (mm)	Target Dimensions (diam. x thick) (mm)	Impactor Dimensions (diam. x thick) (mm)	Buffer Dimensions (diam. x thick) (mm)
C1 (93522)	Al - Al	0.717	54.9	20.5 ne	20.4 ne	0	0	0	a	0.500 x 0.250	38.1 x 19.1	63.5 x 12.7	38.1 x 1.50 np
C2 (93528)	Al - Al	0.728	55.9	20.7 e	20.4 e	0	0	0	a	0.500 x 0.250	38.1 x 19.1	63.5 x 12.7	38.1 x 1.50 np
C3 (93535)	Cu - Cu	0.644	120.5						c	0.400 x 0.250	38.1 x 15.9	50.8 x 6.35	38.1 x 1.58 p
C4 (93539)	Cu - Cu	0.492	86.5	35.7 ne	35.3 ne	0	0.5±0.4	1.1±0.7	c	0.400 x 0.250	38.1 x 15.9	44.5 x 6.35	38.1 x 1.50 p
C5 (93530)	Cu - Al	0.628	67.1	25.5 e	25.1 e	0.4±0.3	0	0	a	0.500 x 0.250	38.1 x 19.1	50.8 x 6.35	38.1 x 1.47 p
C6 (93536)	Cu - Al	0.717	78.6	30.8 ne	29.3 ne	1.4±0.7	1.9±0.5	0	a	0.500 x 0.250	38.1 x 19.1	25.4 x 9.53	38.1 x 1.50 p
C7 (93537)	Cu - Al	0.885	100.2	37.6 e	36.1 e	no (ps)	no (ps)	no (ps)	c	0.500 x 0.250	38.1 x 14.9	38.2 x 6.35	38.1 x 1.50 p
C8 (93532)	Al - Cu	0.631	67.5	22.1 ne	21.9 ne	0.3±0.3	0.7±0.4	0.6±0.3	c	0.500 x 0.250	38.1 x 19.1	63.5 x 12.7	38.1 x 1.50 p

General Comments:

* = Lens coupling, thin aluminum sample   ps = Poor Spectra   no = not observed

e = Elastic Precursor observed   p = Polished buffer plate

ne = Elastic precursor not observed   np = buffer plate Not Polished

Relative Post Impact Intensity	Record Time	Fiber Type	Method of Stripping	Glue Used	Background Increase	Comments
Uniaxial Strain Experiements						
70%	2.55	UV fused Silica	Chemical	Norland 68	none observed	
71%	5.30	NIR fused Silica	mechanical	Norland 68		Spectra are fairly good, counts come back upon release wave arrival
na		Sapphire	na	Norland 68		Sapphire fiber cleaved and polished here using 30, 6, & 1 μm diamond paste, ends weren't without blemises and were probably rounded
30%	1.40	Sapphire	na	Norland 68	none	Intensity diminishes rapidly but the two peaks are clearly discernable, fiber cut and polished by Saphikon
62%	6.00	NIR fused Silica	mechanical	Norland 68		Spectra pretty clean and clear throughout duration of experiment
31%	~3.2	NIR fused Silica	mechanical	Norland 68	none observed	Spectra not very clean, infromation taken from tracks 8,9,10,11,17 only
14%	4.00	NIR fused Silica	mechanical	Norland 68	~4.7 μs	The post impact spectra are poor, information taken from tracks 24 & 30 only
50%	~2.30	NIR fused Silica	mechanical	Norland 68	~2.10 slight	Good spectra while the signal lasts, probably best spectra for a copper target

III Future Work

A. Immediate Goals

1. Examine the sensor response in a variety of materials in the stress range 30-70 kbar
2. Improve on the data acquisition time through the sapphire fiber in the copper matrix.
3. Analyze our existing data to:
    - obtain the stress in the sensor
    - correlate the stress in the sensor with the stress in the matrix (Al)
    - comment on the stress history of an Al target when it is impacted with a rod
4. Automate the process of putting together an experiment.

D. Immediate Experimental Effort

Partt A: Experiments with a-cut ruby chip on fused silica fiber (400 μm)

> *December '93*
> > PMMA Target, Copper Impactor, 40 kbar
> > Aluminum Target, Aluminum Impactor, 40 kbar
> > Calcite Target, Aluminum Impactor, 40 kbar
>
> *Afterwards*
> > Aluminum Oxide loaded epoxy matrix
> > Fused Silica
> > 50 kbar experiments
> > 30 kbar experiments

1.   It is important to obtain as thin a bond as possible between the ruby chip and the optical fiber. Kurt is in the process of building a test jig for this. Our next experiment should be a repeat of C5 (93530: Al target, 67 kbar stress, 6.0 µs recording time achieved). In this repeat experiment we should use a higher time resolution (50ns/track). We should also possibly use the electro-optic modulator so that the ruby chip will only be illuminated 100 ms prior to the arrival of the shock wave. (Apparently this was the procedure followed by Shen in his ruby disk shots which employed the 815 epoxy. Horn, Jin-Kee and Gerry did not use the electro-optic modulator. Gerry used a drop of 815 epoxy the size of a pencil tip and pressed the two disks together in the press without rubbing them. His ruby samples were 0.5" in diameter). We could also bin more pixels in this experiment which would give us an even shorter recording time but would provide a solution to the decrease in the signal by a factor of 2-3 that results from using the electro-optic modulator.

2.   Sapphire fiber experiments.

We have two previous shots with sapphire fibers. In one, the fiber-ruby interface was not ideal (the fiber was polished here). In the second, the fiber had to be pushed through the hole in the matrix to the extent that it dug material from the wall.

It would be useful to use a larger diameter hole (e.g. 40 µm larger than the fiber would require a 460 µm hole diameter). This would make sure that there is epoxy around the fiber to act as cladding.

Additionally, we should measure the luminescence signal from the fiber impurity before every experiment and we should get an idea of the numerical aperture of the fiber as compared to the fused silica.

3.   Rod impact experiments

4.   Shot with fused silica fiber in fused silica matrix at ~ 50 kbar. This perfectly matches the shock impedance of the fiber to the matrix. The experiment would allow us to test the possibility that the lateral boundary between the fiber and the matrix plays a role in the observed intensity decrease. It would also give us results on a third material and can be used as a useful preparation to a shot in the range 60-90 kbar.

5.   Investigate the possibility of using other fibers, e.g., quartz.

E. Long - term goals

1. Use the sensor to study the response of a wide variety of materials under different conditions (e.g. uniaxial strain, rod impact): stainless steel, marble, fused silica, PMMA, nitromethane, epoxy.

2. Extend capability to low stresses: need to increase the dispersion on the spectrometer or to implement a new technique (e.g. hole - burning).

3. Streamline the data analysis to obtain the stress state of the sensor (and matrix) into a routine procedure.

Appendix A

Detailed experimental results: Diagnostic Experiments
A1: 93544
A2: 93545

Date: 11/19/93

Shot No.   93-544

Experimental Configuration and Specifications:

Experimentalist:	Kurt Zimmerman
Type of Experiment:	Uniaxial Strain, Lens Coupling
Stress:	120 kbar
R-Line Duration:	~1.5 μs
Post Shock Intensity:	71% steady (compression)
Time/Track:	54.5 ns
Impact Velocity:	0.525 mm/μs
Ruby Orientation:	C-cut
Ruby Dimensions:	19 mm diameter x 0.250 mm thick
method of manufacture:	cut and polished by Insaco
Optical Fiber:	Lens Coupled
material/diameter:	UV Fused Silica
method of stripping:	na
epoxy used for bond:	Norland Optical Adhesive #68
Target Material:	Ruby
Target Dimensions:	same as ruby dimensions
Buffer Material/Thickness:	na
polished (y/n):	na
Impactor Material:	Sapphire
Impactor Dimensions:	25.4 mm diameter x 1.59 mm thick

Remarks:

This shot was a room temperature shot prepared the same way as previous low temperature shots by Gerry Pangilinan, Jin-Kee Hyun, Shen, ect. The purpose of the shot was to determine if the Norland Optical Adhesive #68, used in the bonding of the ruby to the sapphire, makes a contribution to the loss of counts upon shock compression. The preparation of the shot was similar to the low temperature shots, with the same type of cell used except that the Indium O-ring was not used and the sample was not cooled. The epoxy was degassed before application to a cleaned A-cut sapphire substrate (1.25" diameter x 0.125" thick). The ruby chip was placed on the sapphire substrate and rubbed down. Following this, a clamp was used to apply pressure to the bond for ~½ hour. Subsequently, the ruby/sapphire sample was placed under a UV lamp for ~1½ hours for curing. The specimen was then placed in a 50°C oven overnight for final curing. The bond was measured to be -2.4 μm ± 3.8 μm. I noticed that the outside ~1 mm of the ruby had no epoxy under it but that inside this area the epoxy was uniform. The amplitude in the compression region was 71% of that at ambient conditions for both the R1 and R2 lines. There was no perceptible change in the widths of the lines. The R-line separation in the compressed region was -2.4 Å ± 0.3 Å.
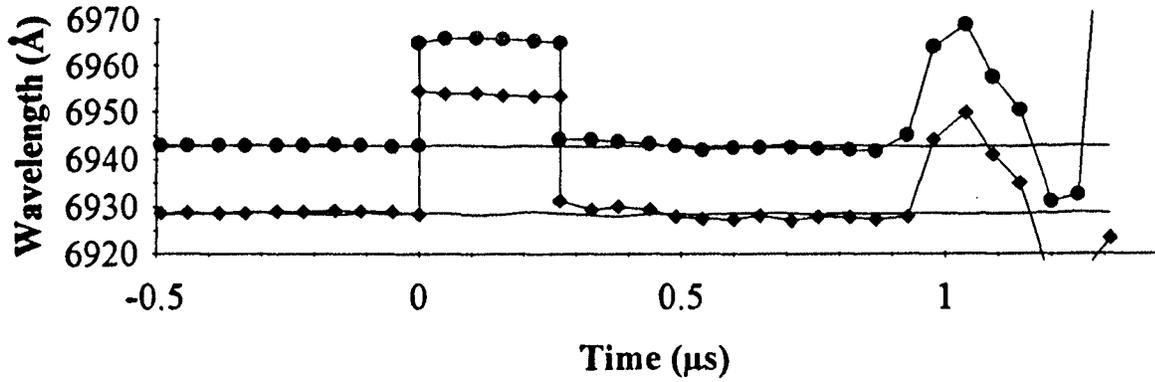
L Mem: 1, Trk: 13, C: 263, X: 263, Magnitude: 7,217
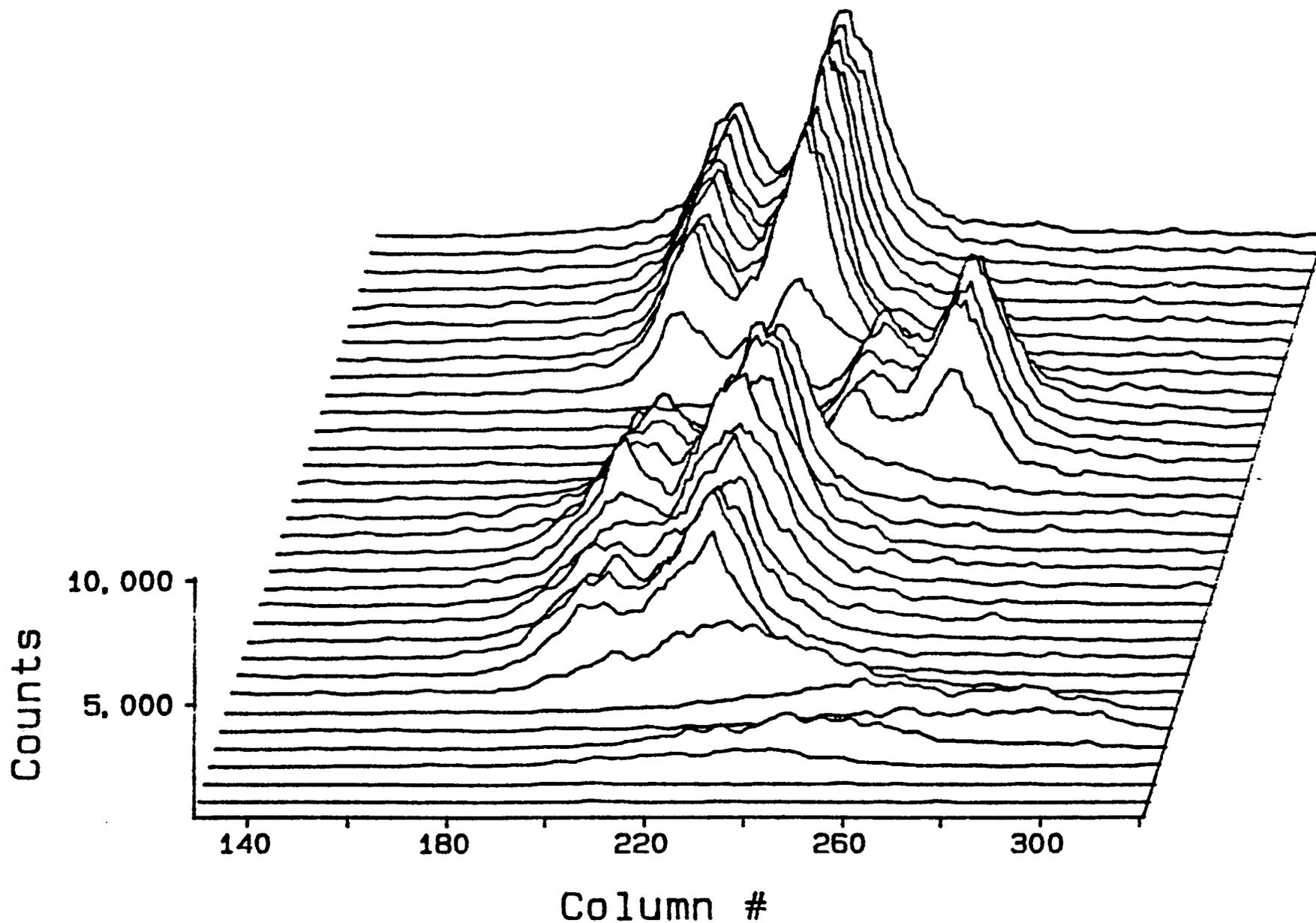
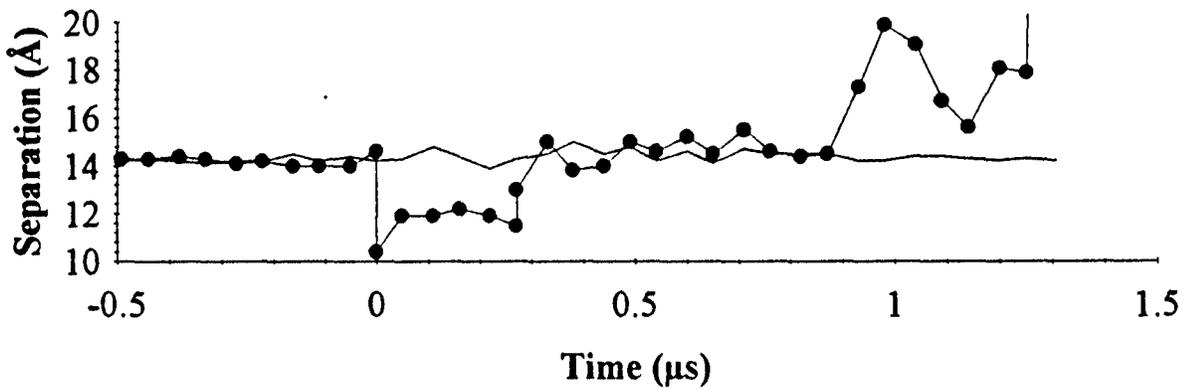SHOT #93-544 120 kbar C-cut ruby disc Norland Adhesive #68

R-Line Peak Position vs. Time
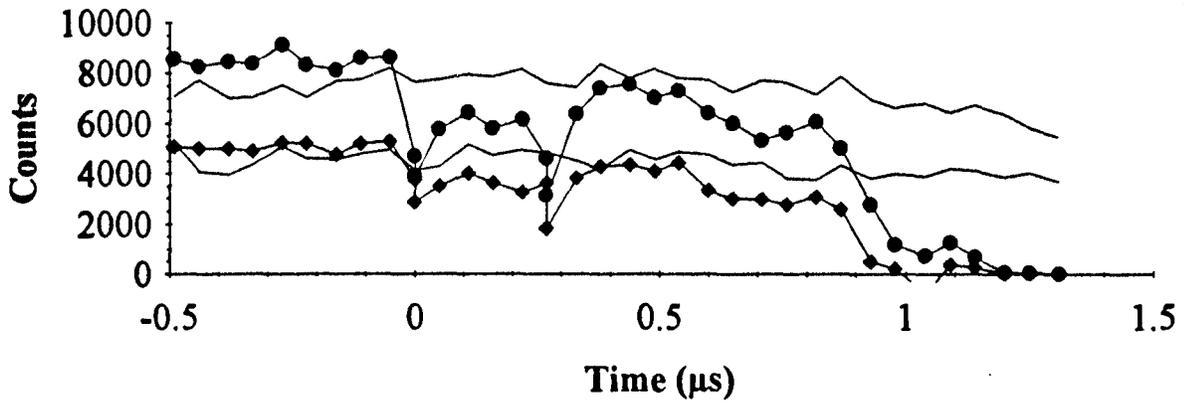
Wavelength (Å)

6970
6960
6950
6940
6930
6920

-0.5   0   0.5   1

Time (µs)

R-Line Separation vs. Time

Separation (Å)

20
18
16
14
12
10

-0.5   0   0.5   1   1.5

Time (µs)

R-Line Intensity vs. Time

Counts

10000
8000
6000
4000
2000
0

-0.5   0   0.5   1   1.5

Time (µs)

Date: 12/1/93

Shot No.   93-545

Experimental Configuration and Specifications:

Experimentalist: Kurt Zimmerman
Type of Experiment: Uniaxial Strain, Lens Coupled
Stress: 122.8 ±2 kbar
R-Line Duration: ~260 compression, full release
Post Shock Intensity: 71% for R1, 73% for R2
Time/Track: 52.2 ns
Impact Velocity: 0.539 ±0.012 mm/µs
Ruby Orientation: C
Ruby Dimensions: 19.1 mm diameter x 0.250 mm thick
    method of manufacture: cut by Insaco
Optical Fiber:
    material/diameter: UV Fused Silica
    method of stripping: na
    epoxy used for bond: 815 epoxy
Target Material: Ruby
Target Dimensions: 19.1 mm diameter x 0.25 mm thick Sapphire backed
Buffer Material/Thickness: na
    polished (y/n):   na
Impactor Material: Sapphire
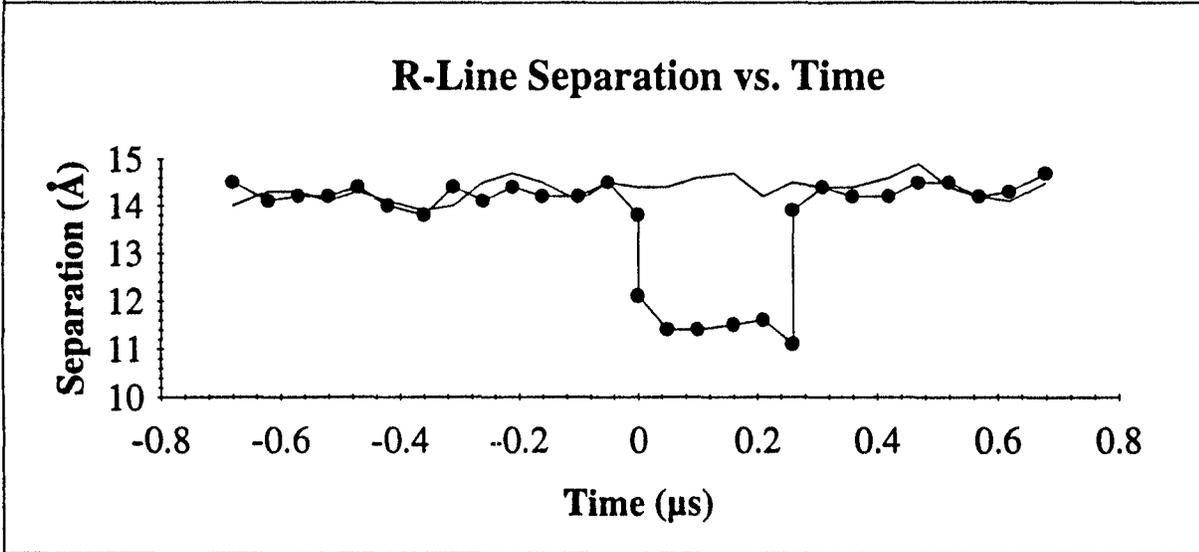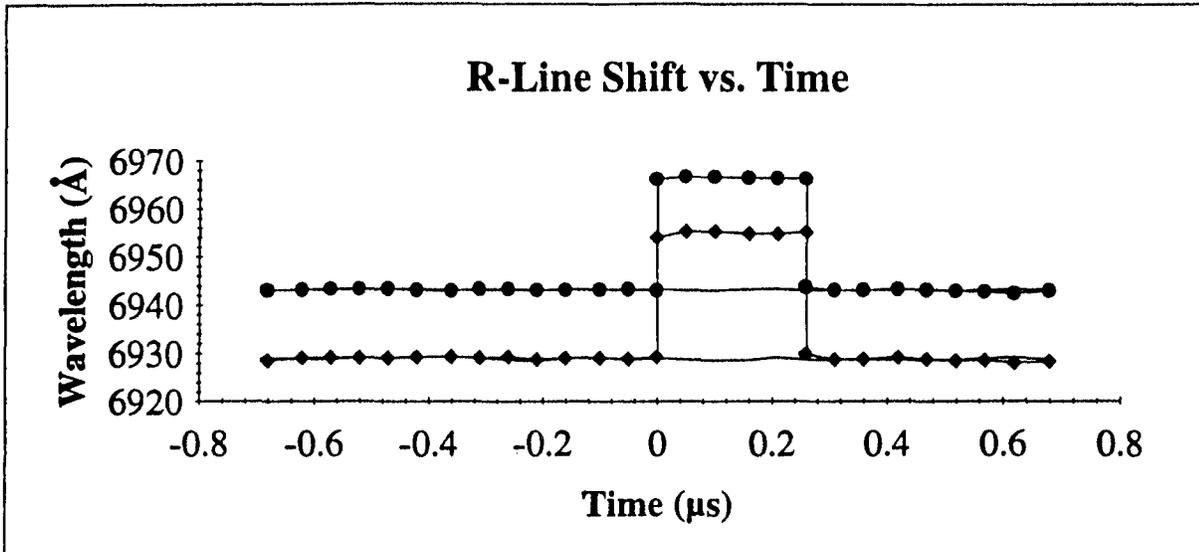Impactor Dimensions: 25.4 mm diameter x 1.59 mm thick

Remarks:

This shot was a room temperature shot prepared the same way as the previous
shot #93-544. The purpose of the shot was to compare the data obtained with the
previous shot which used a different epoxy. The preparation of the shot was the
same as shot #93-544. The epoxy was degassed before application to a cleaned
A-cut sapphire substrate (1.25" diameter x 0.125" thick). The ruby chip was
placed on the sapphire substrate and rubbed down, following which a clamp was
used to apply pressure to the bond for ~½ hour. The sample was left to cure
overnight before anything else was done. The bond was measured to be 1.8 µm ±
1.5 µm. Similar to shot # 93-544, I noticed that the outside ~1 mm of the bond
had no epoxy under it but that in side this area the epoxy was uniform. The
amplitude in the compression region was 71% of that at ambient conditions for
the R1 line and 73% ambient for the R2 line. There was no perceptible change in
the widths of the lines. The R-line separation in the compressed region was -3.0
Å ± 0.3 Å. The compression shift was ~23.3 Å for R1 and ~26.3 Å. The bottom
line is that the UV curing epoxy can be used without changing the outcome of the
experiment.

L Mem: 1, Trk: 14, C: 263, X: 263, Magnitude: 6,020

Counts

10,000

5,000

←impact

Time→

140   180   220   260   300
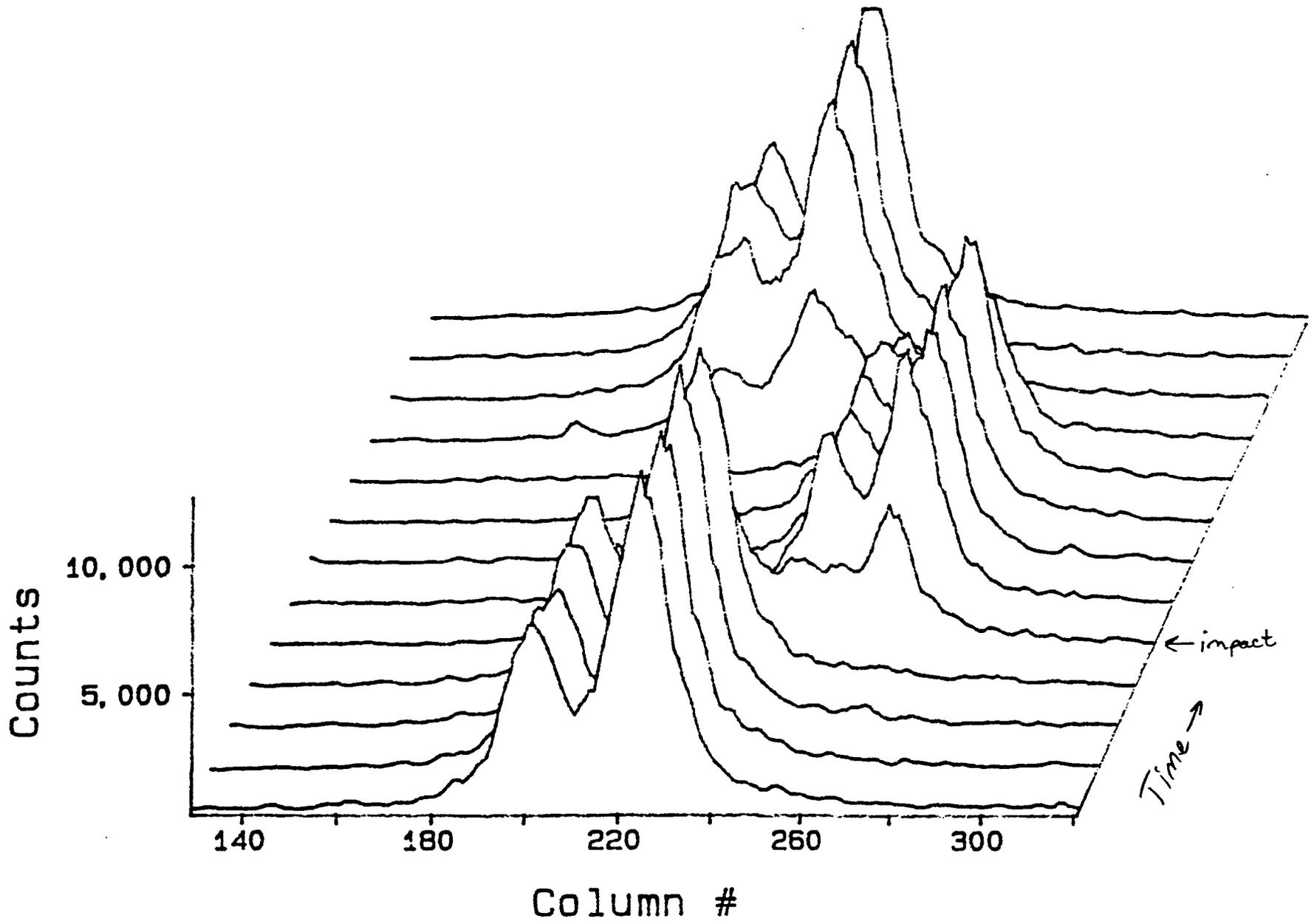
Column #

12/1/93 C-CUT RUBY DISC SHOT USING 815 EPOXY

R-Line Shift vs. Time

R-Line Separation vs. Time

R-Line Intensity vs. Time
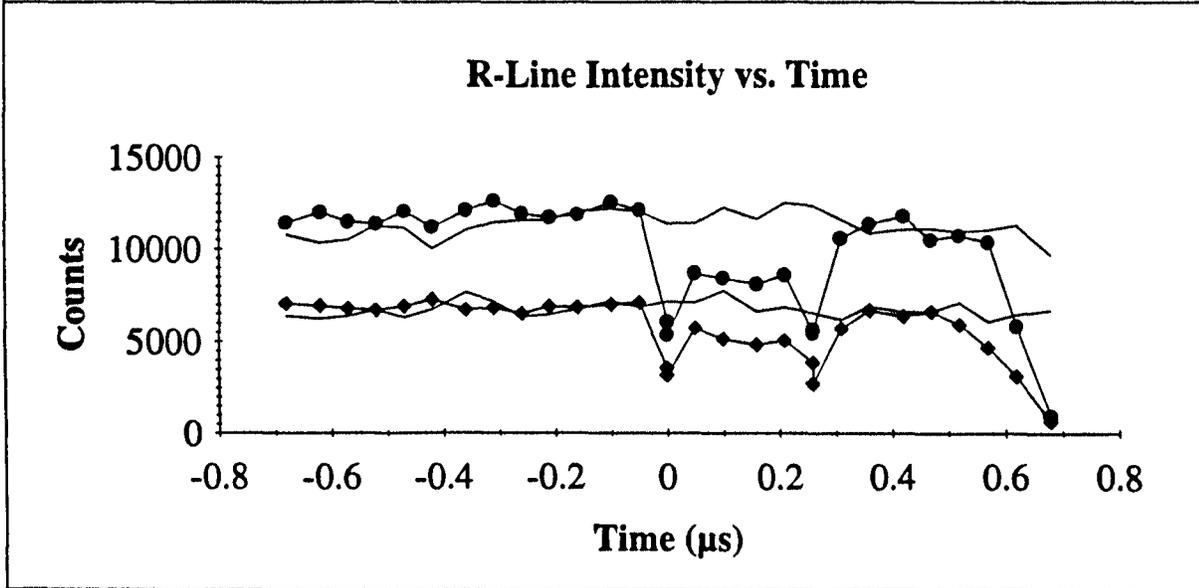
Appendix B

Detailed experimental results: Preliminary Experiments

B1: 93508

B2: 93510

B3: 93515

B4: 93518

Date: 3/9/93

Shot No.   93-508

Experimental Configuration and Specifications:

Experimentalist:	Kurt Zimmerman
Type of Experiment:	Uniaxial Strain, Lens Coupled
Stress:	54.1 kbar
R-Line Duration:	~1.4 μs
Post Shock Intensity:	27%, steady decrease
Time/Track:	100 ns
Impact Velocity:	0.707 mm/μs
Ruby Orientation:	C-cut
Ruby Dimensions:	1.040 mm diameter x 0.250 mm thick
method of manufacture:	Cut using Impact Grinder (rough edges)
Optical Fiber:	
material/diameter:	(lens coupled)
method of stripping:	na
epoxy used for bond:	815 Epoxy
Target Material:	Al (31.7 mm diam. x 3.175 mm sapphire backing)
Tartget Dimensions:	31.7 mm diameter x 0.250 mm thick
Buffer Material/Thickness:	no buffer
polished (y/n):	na
Impactor Material:	Al
Impactor Dimensions:	22.2 mm diameter x 15.2 mm thick

Remarks:

This was the first ruby chip shot. The sapphire backing seems to make a difference in the initial shift. The signal is dirty and the two peaks are not distinguishable initially. However, after a couple of tracks the spectra become clearer and 2 peaks are seen. At impact there is a slightly higher background signal that goes away quickly. The release wave came in after ~600 ns at which point the R-line peaks are a little better defined.

Date: _3/9/93_

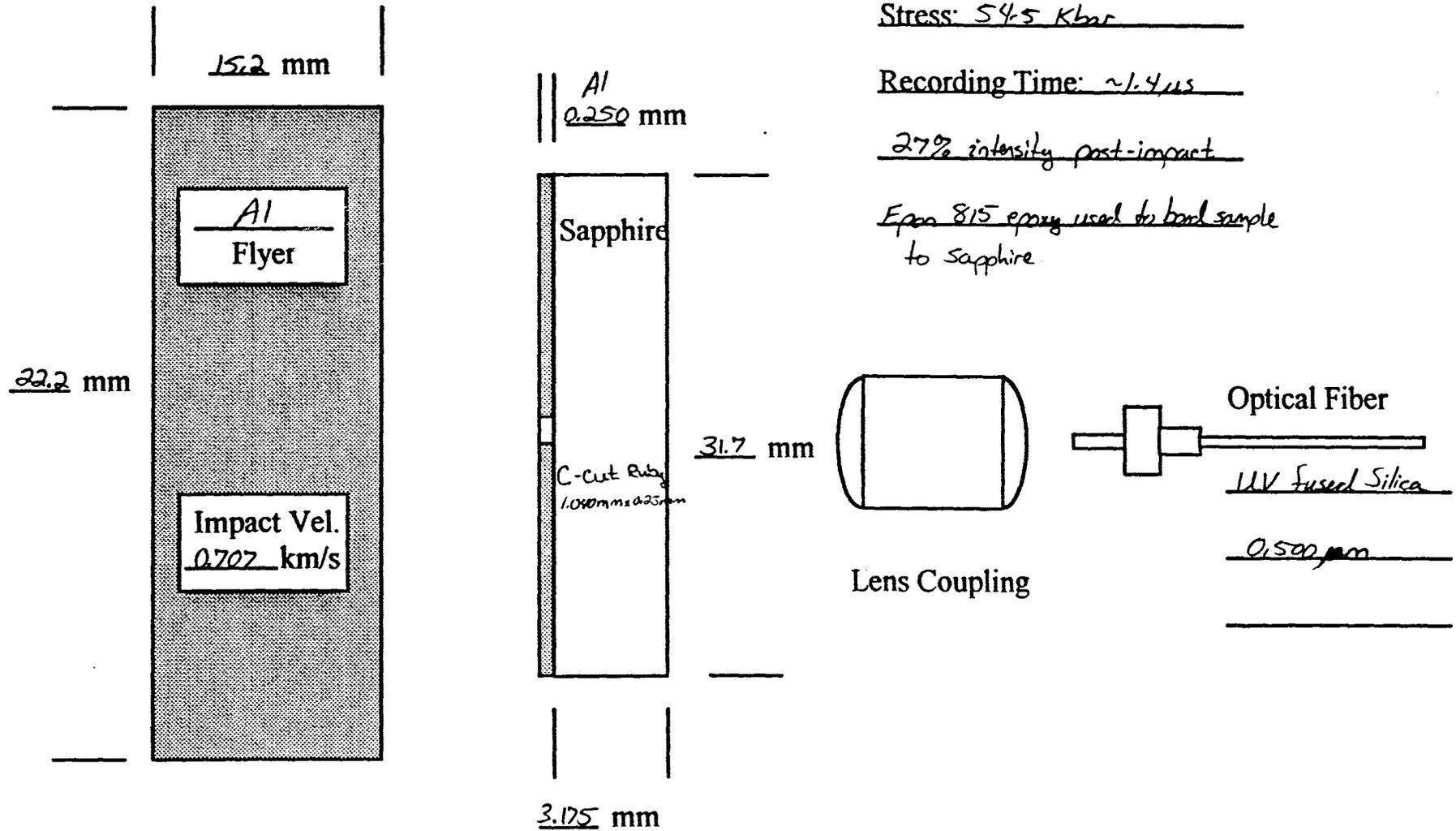# Experimental Configuration for the Ruby Chip Sensor
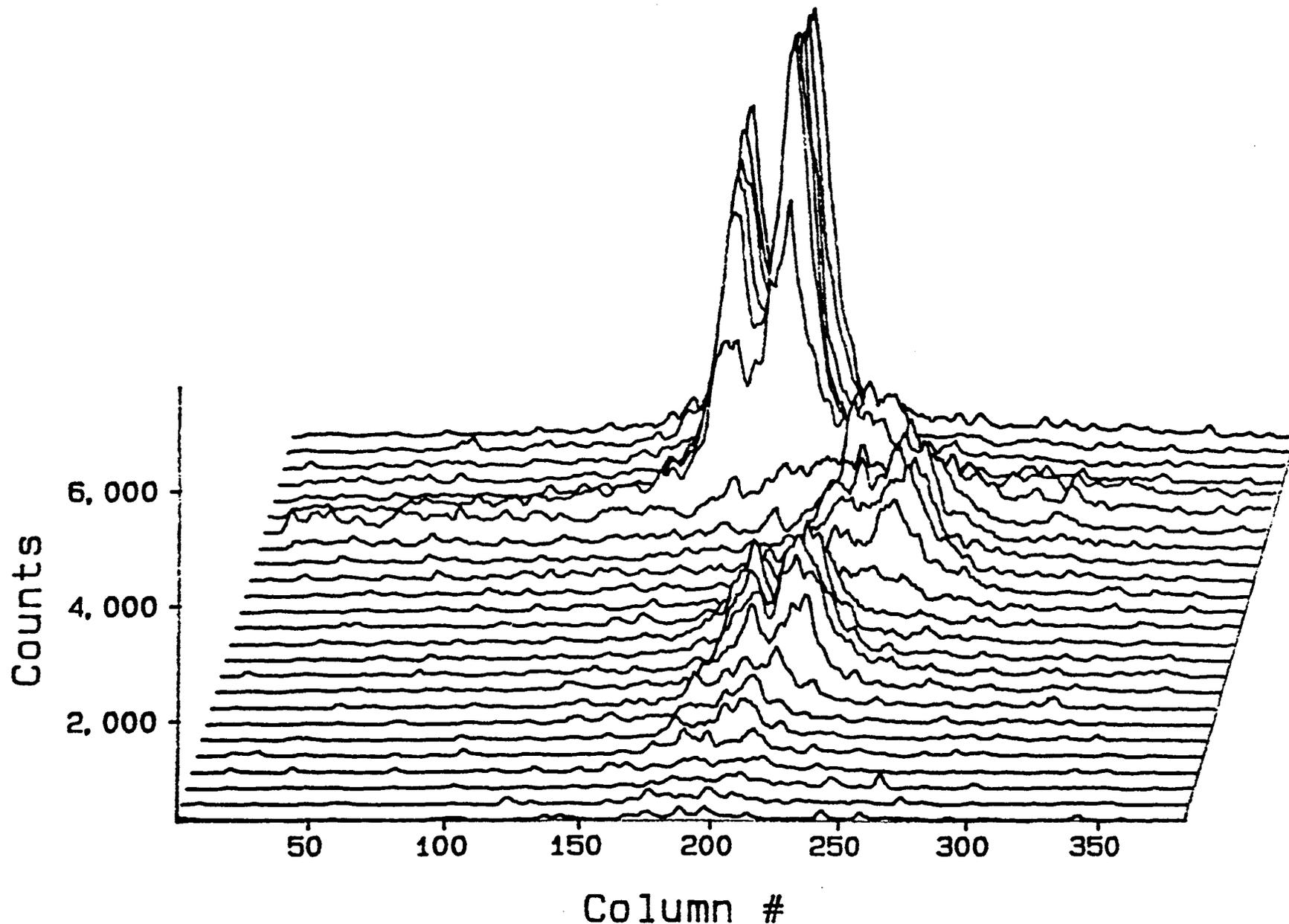## Shot No. _93-508_

Comments:

Stress: _545 Kbar_

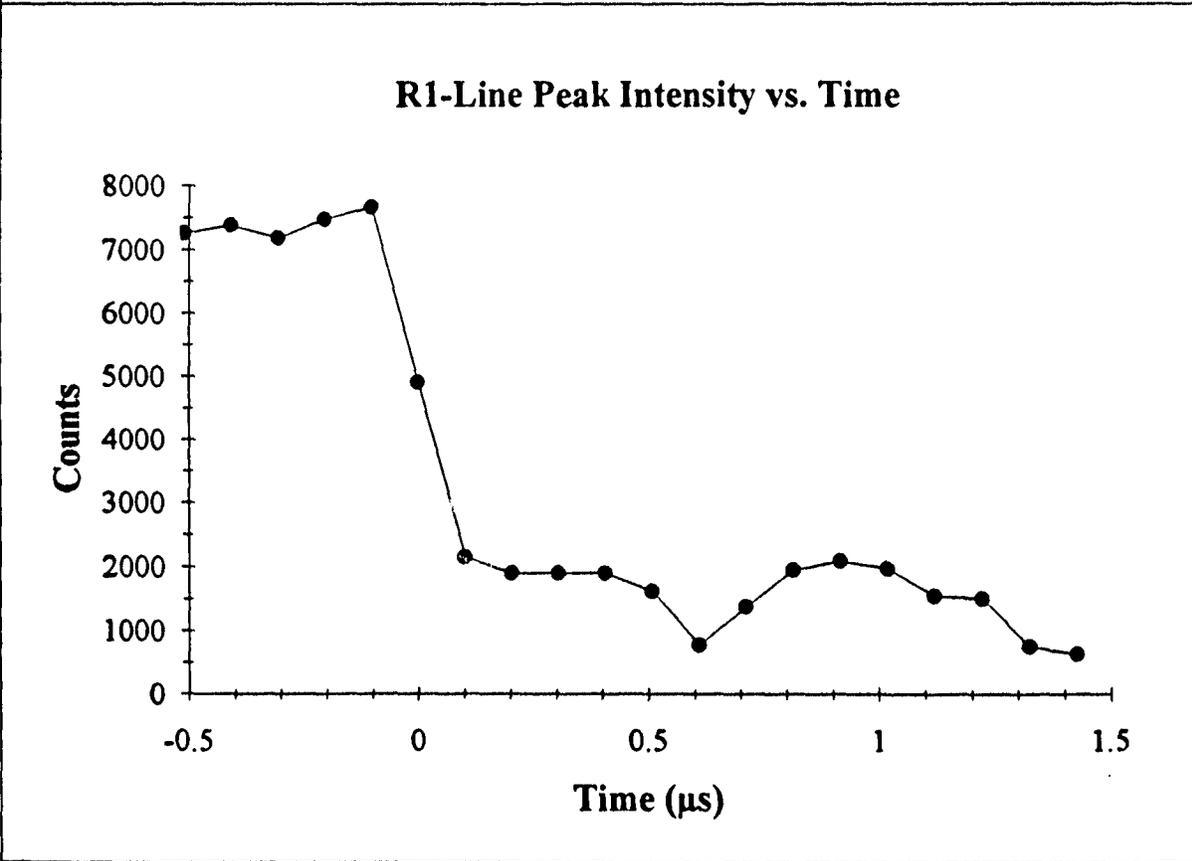Recording Time: _~1.4 μs_

27% intensity post-impact

Epon 815 epoxy used to bond sample to Sapphire

_15.2_ mm

| Al |
| Flyer |

_22.2_ mm

| Impact Vel. |
| _0.707_ km/s |

Al
_0.250_ mm

Sapphire

C-Cut Ruby
_1.050 mm × 0.25 mm_

_31.7_ mm

Lens Coupling

Optical Fiber

UV Fused Silica

_0.500 μm_

_3.175_ mm

O: SHOT.DAT Mem: 1, Trk: 1, C: 0, X: 0, Magnitude: 322

SHOT 93-508 1mm C-CUT RUBY IN THIN Al WAFER

R-Line Peak Position vs. Time

R1-Line Peak Intensity vs. Time
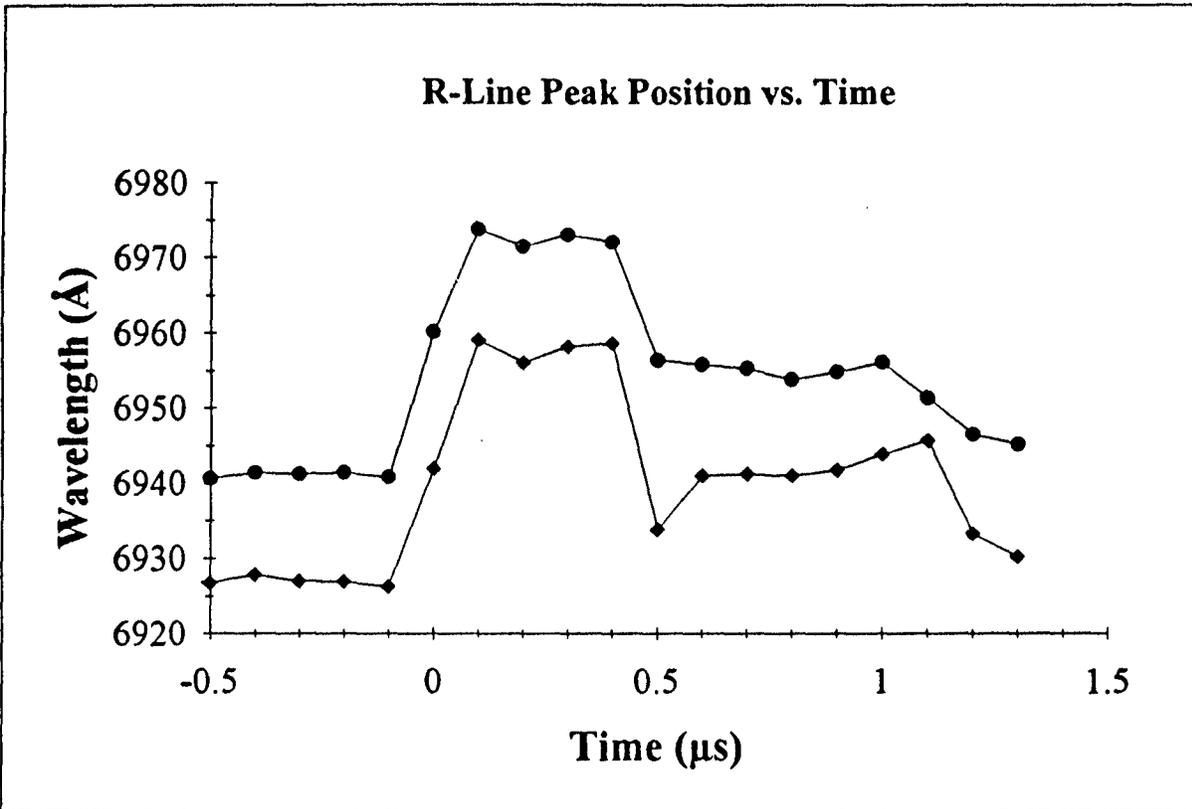
Date: 3/17/93

Shot No. 93-510

Experimental Configuration and Specifications:

Experimentalist: Kurt Zimmerman
Type of Experiment: Uniaxial Strain, Lens Coupled
Stress: 53.8 kbar
R-Line Duration: ~1.8 μs
Post Shock Intensity: 56 % steady decrease
Time/Track: 50 ns
Impact Velocity: 0.704 mm/μs
Ruby Orientation: C-cut
Ruby Dimensions: 1.040 mm diameter x 0.250 mm thick
    method of manufacture: Cut using Impact Grinder
Optical Fiber:
    material/diameter: (lens coupled)
    method of stripping: na
    epoxy used for bond: 815 Epoxy
Target Material: Al (31.7 mm diam. x 3.175 mm sapphire backing)
Tartget Dimensions: 31.7 mm diameter x 0.250 mm thick
Buffer Material/Thickness: none
    polished (y/n): na
Impactor Material: Al
Impactor Dimensions: 22.2 mm diameter x 15.2 mm thick

Remarks:

The results were much the same as shot #93-508. The signal was significantly cleaner however and lasted slightly longer. The two peaks are observable most of the time. The peaks got much lower in counts and not well defined for a couple of tracks when there was an increase or decrease in stress, but the counts would recover to approximately 50% of the ambient value. There was no background increase seen over the duration of the experiment. I felt better about the quality of construction on this target versus the previous shot.

Date: _3/17/93_

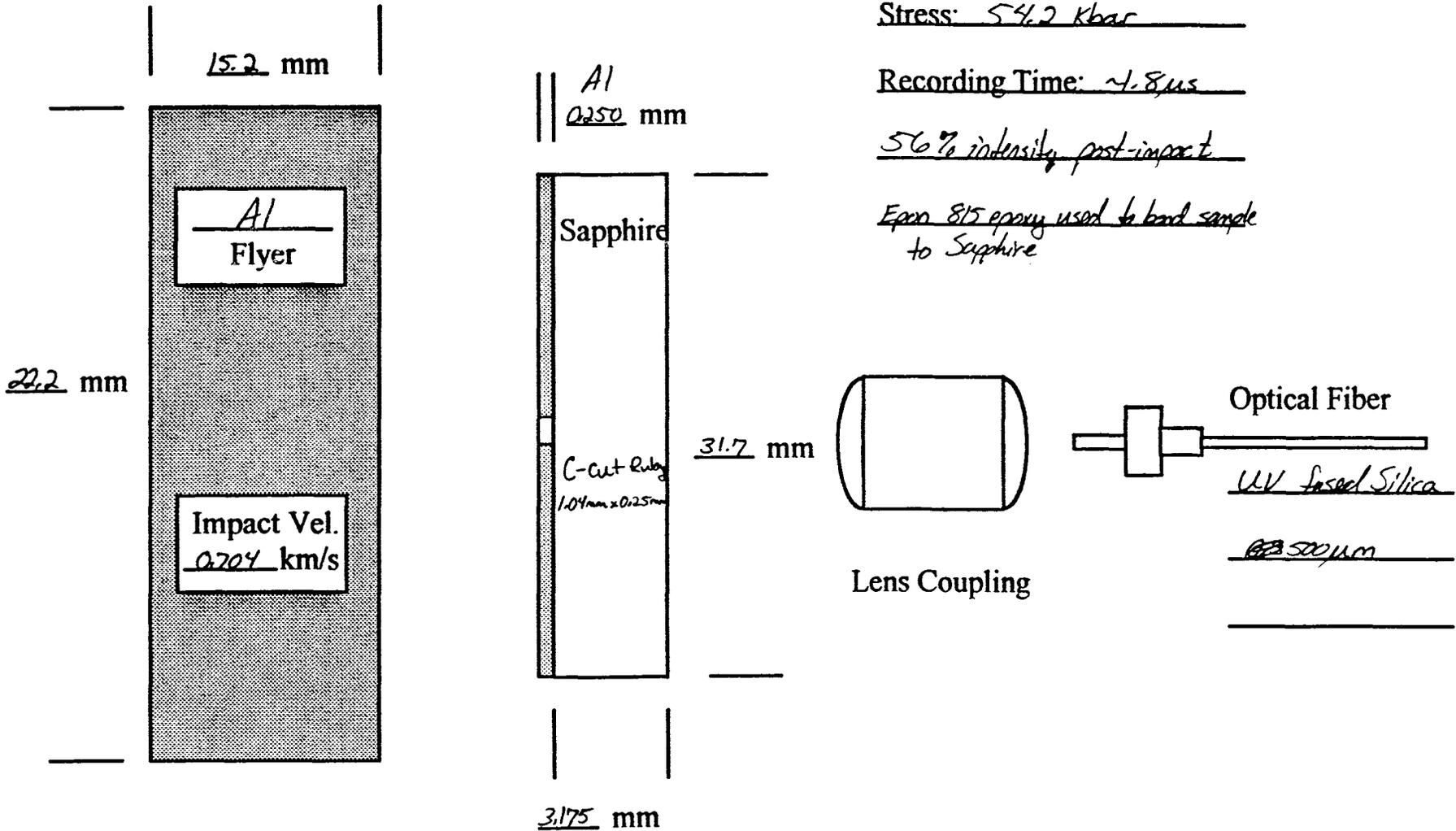# Experimental Configuration for the Ruby Chip Sensor
Shot No. _93-510_

Comments:

Stress: _54.2 Kbar_

Recording Time: _~1.8μs_

56% intensity post-impact

Epon 815 epoxy used to bond sample to Sapphire

_15.2_ mm

_Al_
Flyer

_22.2_ mm

Impact Vel.
_0.704_ km/s

_Al_
_0.250_ mm

Sapphire

_31.7_ mm

C-cut Ruby
_1.04mm x 0.25mm_

_3.175_ mm

Lens Coupling

Optical Fiber

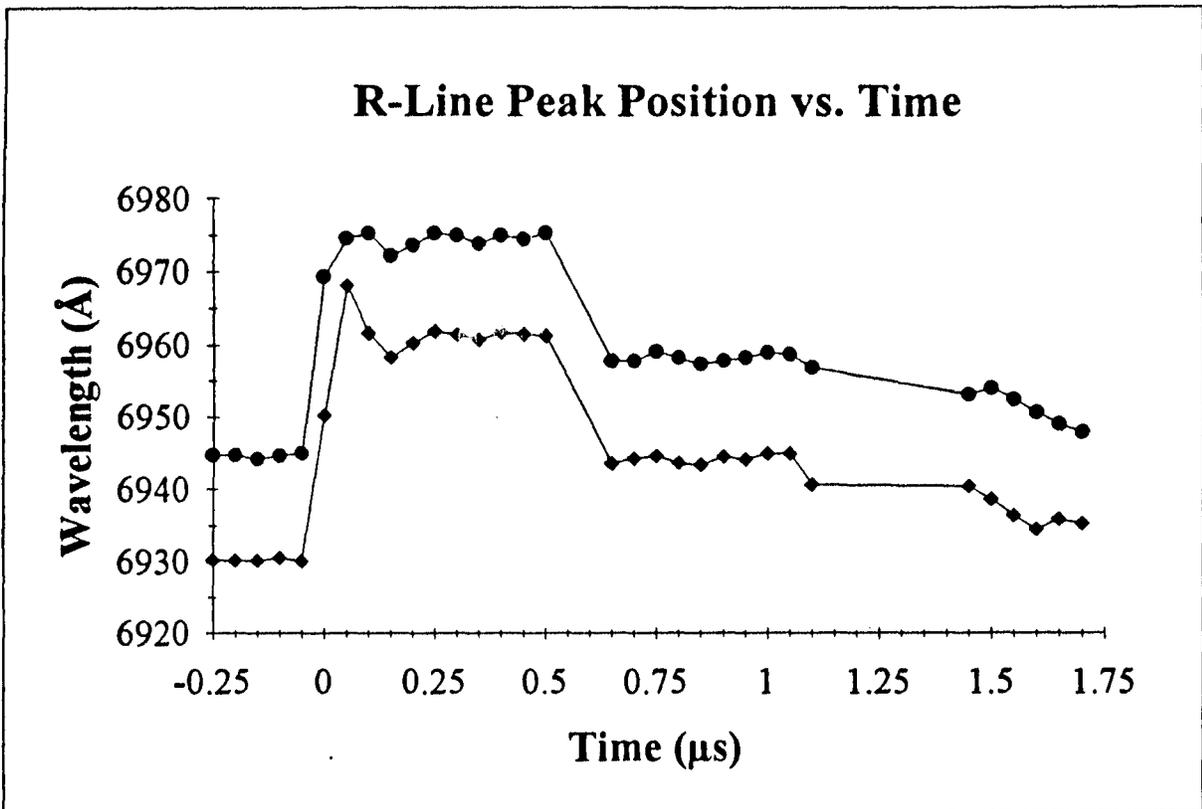_UV fused Silica_

_Ø 500μm_

3/17/93   Shot #93-510 ruby chip embedded in Aluminum
Entrance slit ~200μm, exit setting @~46, f₁ laser power, ~50ns/track
O: SHOT.DAT Mem: 1, Trk: 27, C: 200, X: 200, Magnitude: 1.562
shift begins on track 5, release starts track 15
total time data seen after shock is ~1.8μs

R-Line Peak Position vs. Time

R1-Line Peak Intensity vs. Time
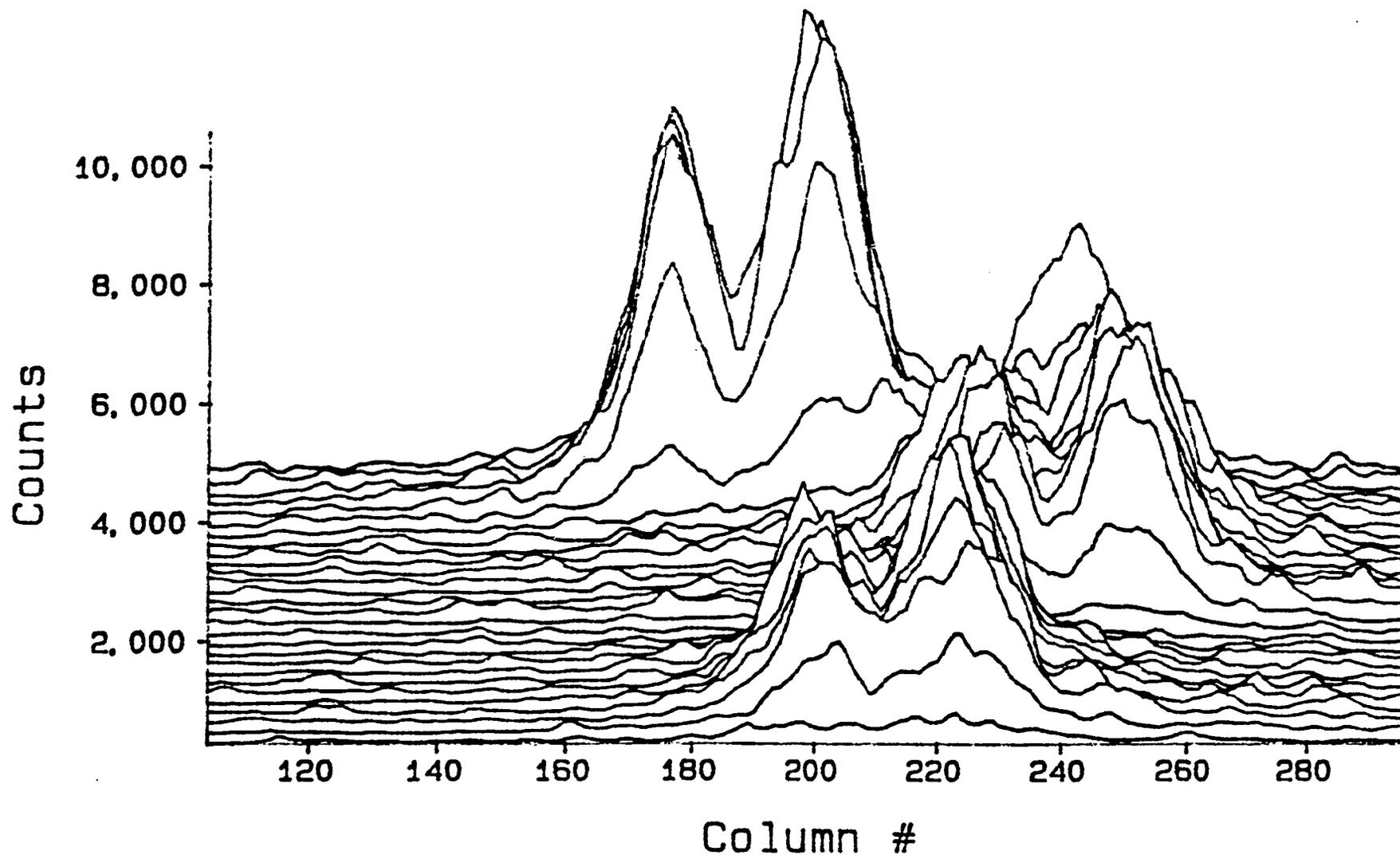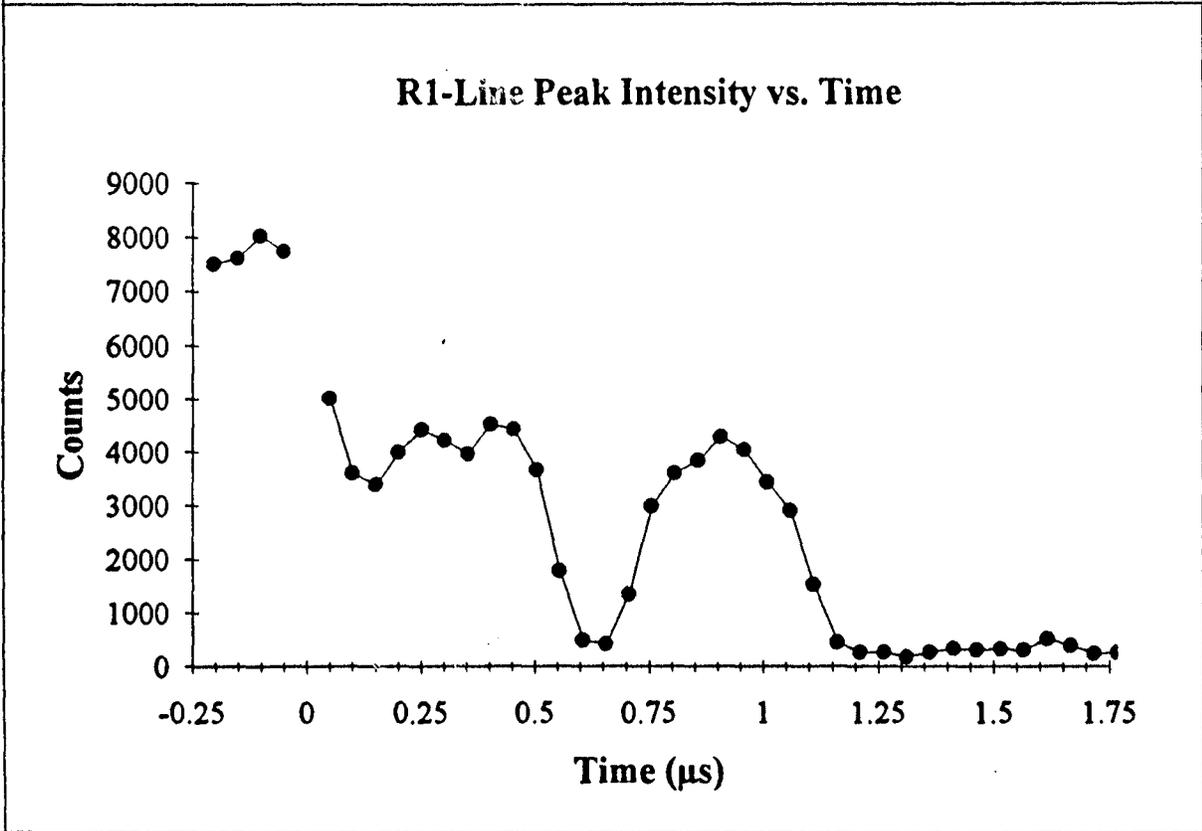
Date: 4/26/93

Shot No. 93-515

Experimental Configuration and Specifications:

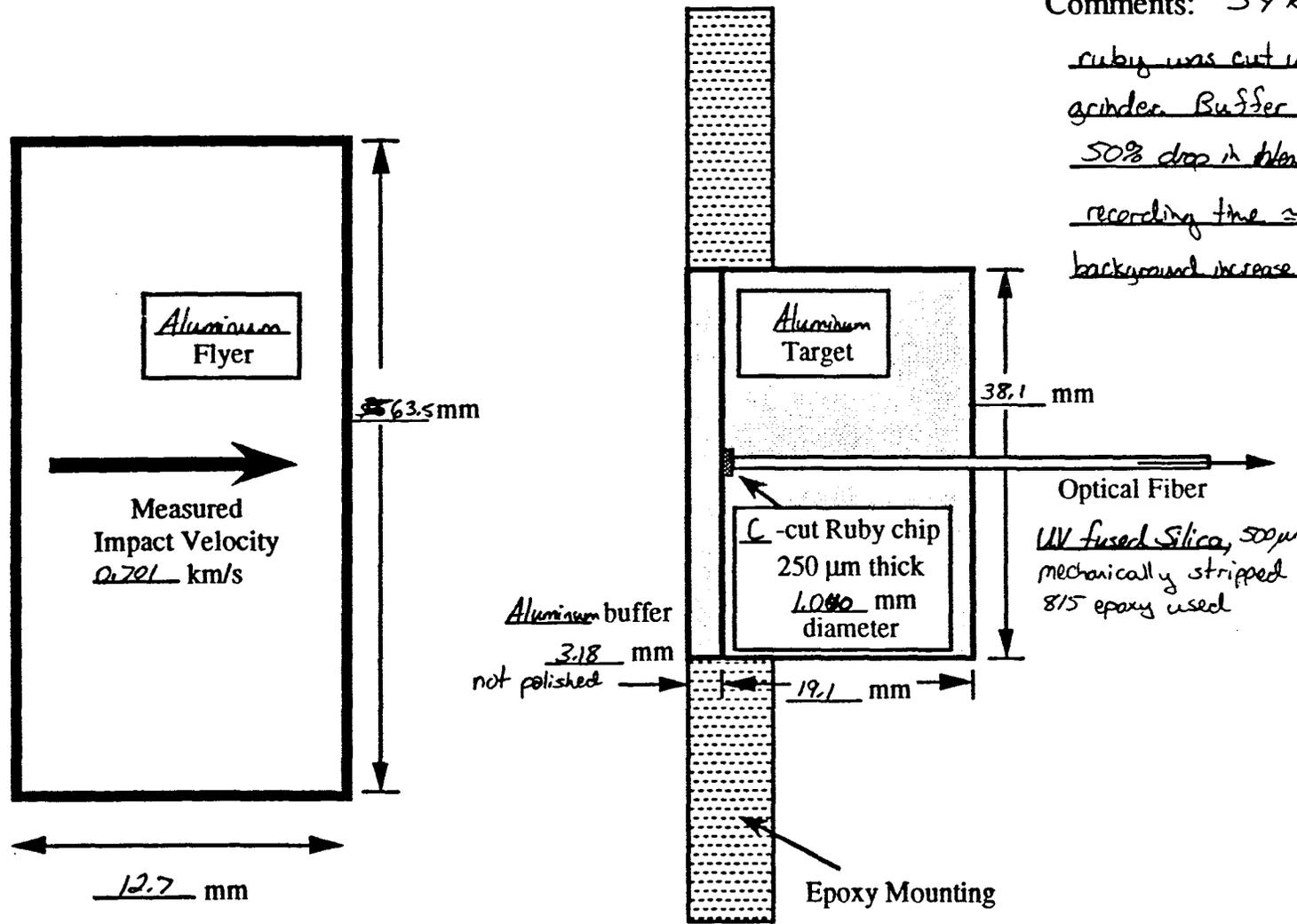|	
Experimentalist:	Kurt Zimmerman
Type of Experiment:	Uniaxial strain, Direct Coupling
Stress:	53.5 kbar
R-Line Duration:	~3.8 µs
Post Shock Intensity:	50% steady decrease
Time/Track:	100 ns
Impact Velocity:	0.701 mm/µs
Ruby Orientation:	C-cut
Ruby Dimensions:	1.040 mm diameter x 0.250 mm thick
method of manufacture:	Cut using Impact Grinder (rough edges)
Optical Fiber:	
material/diameter:	UV Fused Silica / 500 µm
method of stripping:	mechanical
epoxy used for bond:	815 Epoxy
Target Material:	Al
Target Dimensions:	38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness:	Al / 3.18 mm thick
polished (y/n):	n
Impactor Material:	Al
Impactor Dimensions:	63.5 mm diameter x 12.7 mm thick

Remarks:

Best results to date. In the first track after impact the signal appears to be very broad - but is distinct following this. After ~2.9 µs the peaks begin to shift back towards their ambient positions. The peak amplitude steadily decreases after impact until the signal is completely gone. After ~2.6 µs there is a uniform background increase. The signal is still present but diminishes in intensity. This background stays over the rest of the duration of the experiment. The ruby chip was ~10 µm above the surface of the target. The bond thicknesses between the ruby chip and the fiber as well as the buffer plate and the target are unknown. The ruby chip was glued to the fiber and into the target material at the same time. I attempted to put a small amount of pressure on the ruby chip but I am unaware of how successful I was. I did not observe the fiber ruby interface following the assembly.

Date: 7/26/93

Experimental Configuration for the Ruby Chip Sensor
Shot No. _93-515_

Aluminum
Flyer

Measured
Impact Velocity
_0.701_ km/s

$\cancel{55}$63.5 mm

_12.7_ mm

Aluminum
Target

38.1 mm

Optical Fiber

UV fused Silica, 500μm
mechanically stripped
8/5 epoxy used

_C_-cut Ruby chip
250 μm thick
_1.060_ mm
diameter

Aluminum buffer
_3.18_ mm
not polished

_19.1_ mm

Epoxy Mounting

1: SHOT.DAT Mem: 1, Trk: 41, C: 99, X: 99, Magnitude: 878

R-Line Peak Position vs. Time

R1-Line Peak Intensity vs. Time
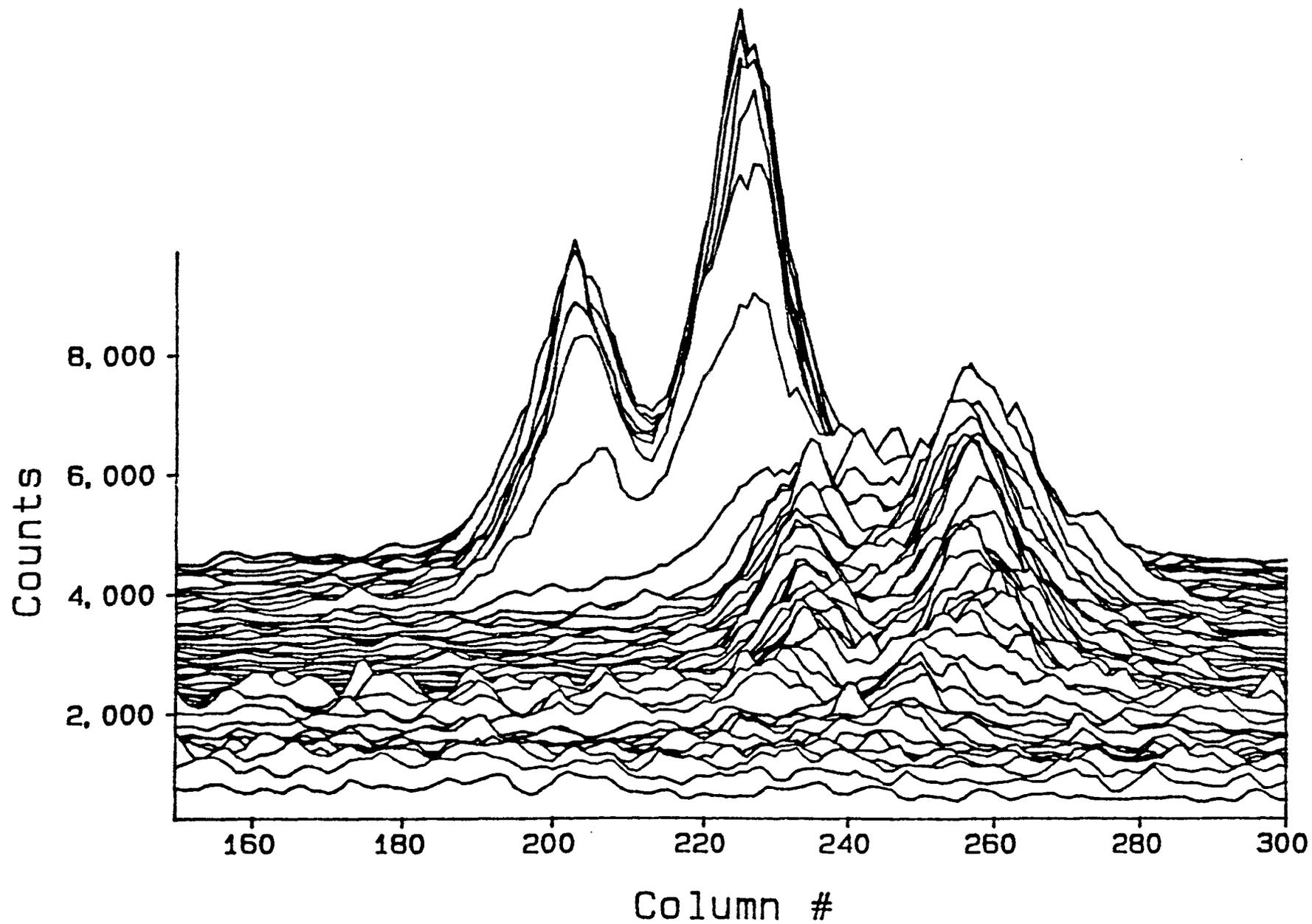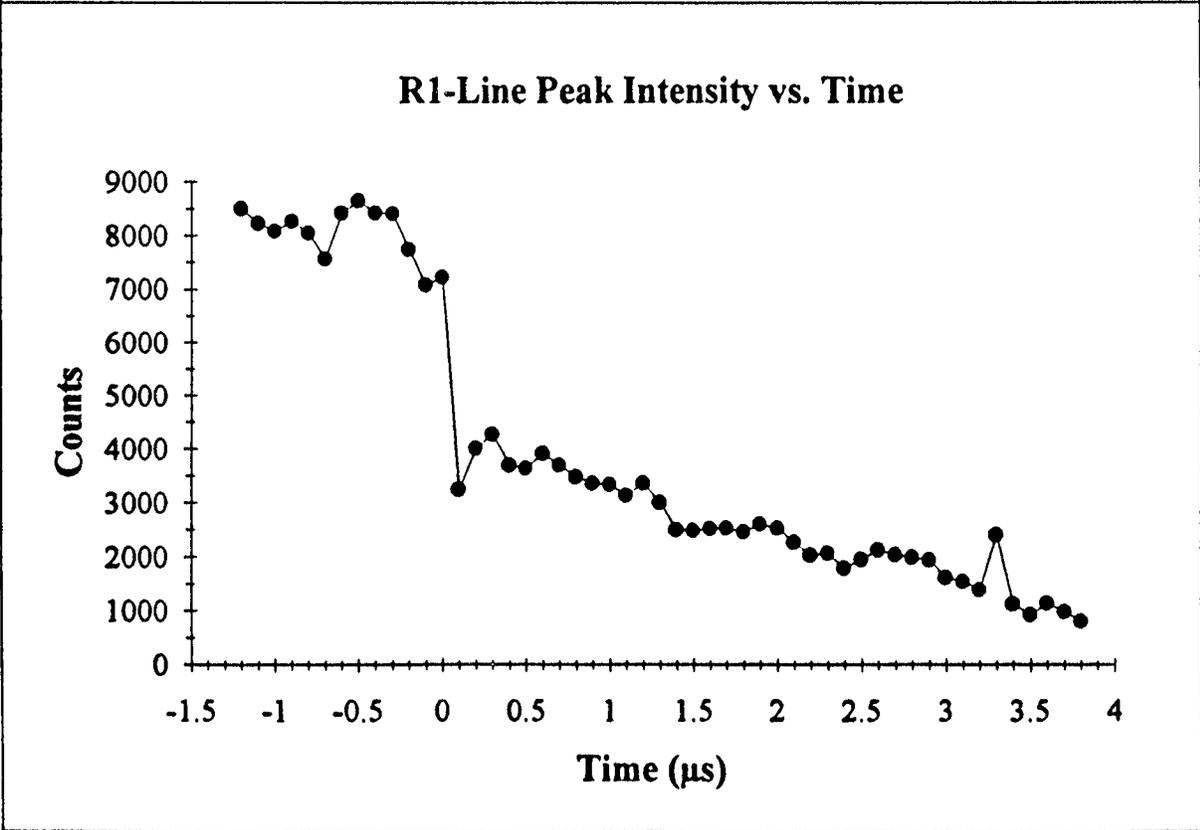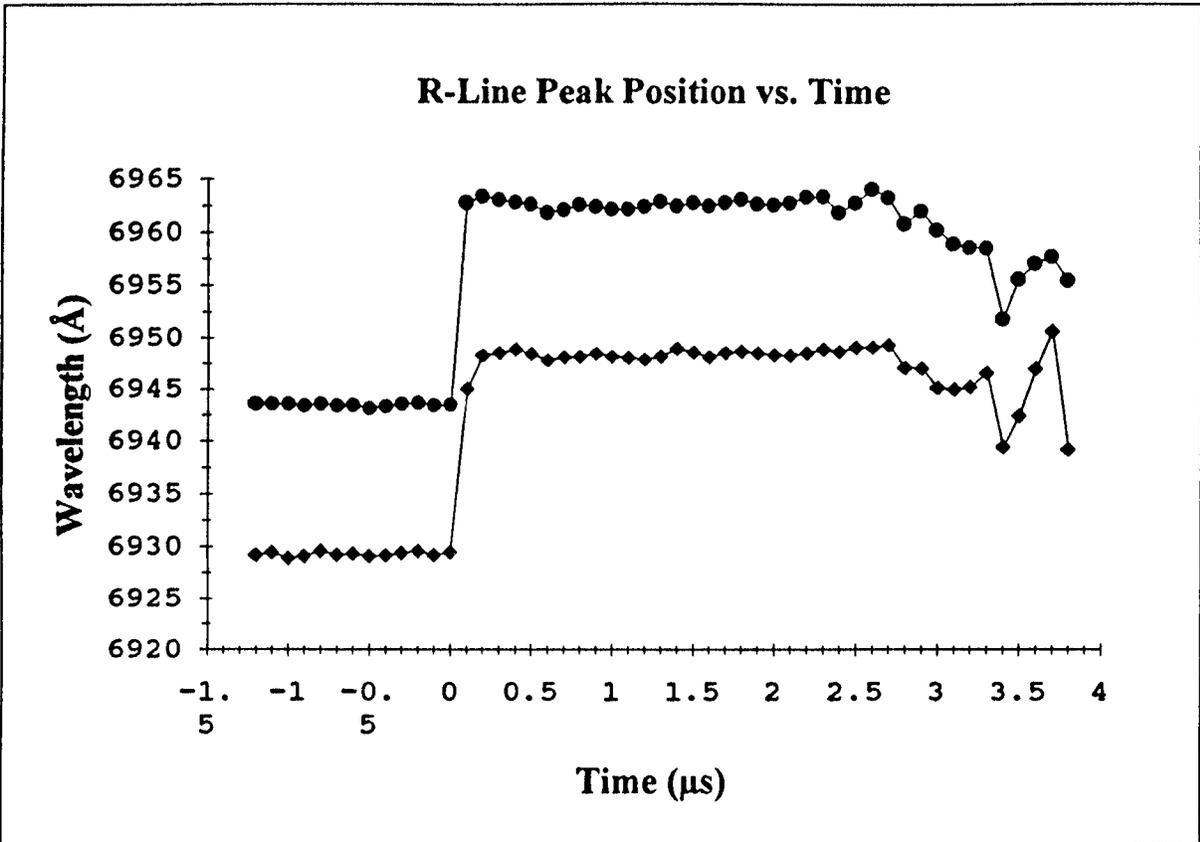
Date: 5/10/93

Shot No.   93-518

Experimental Configuration and Specifications:

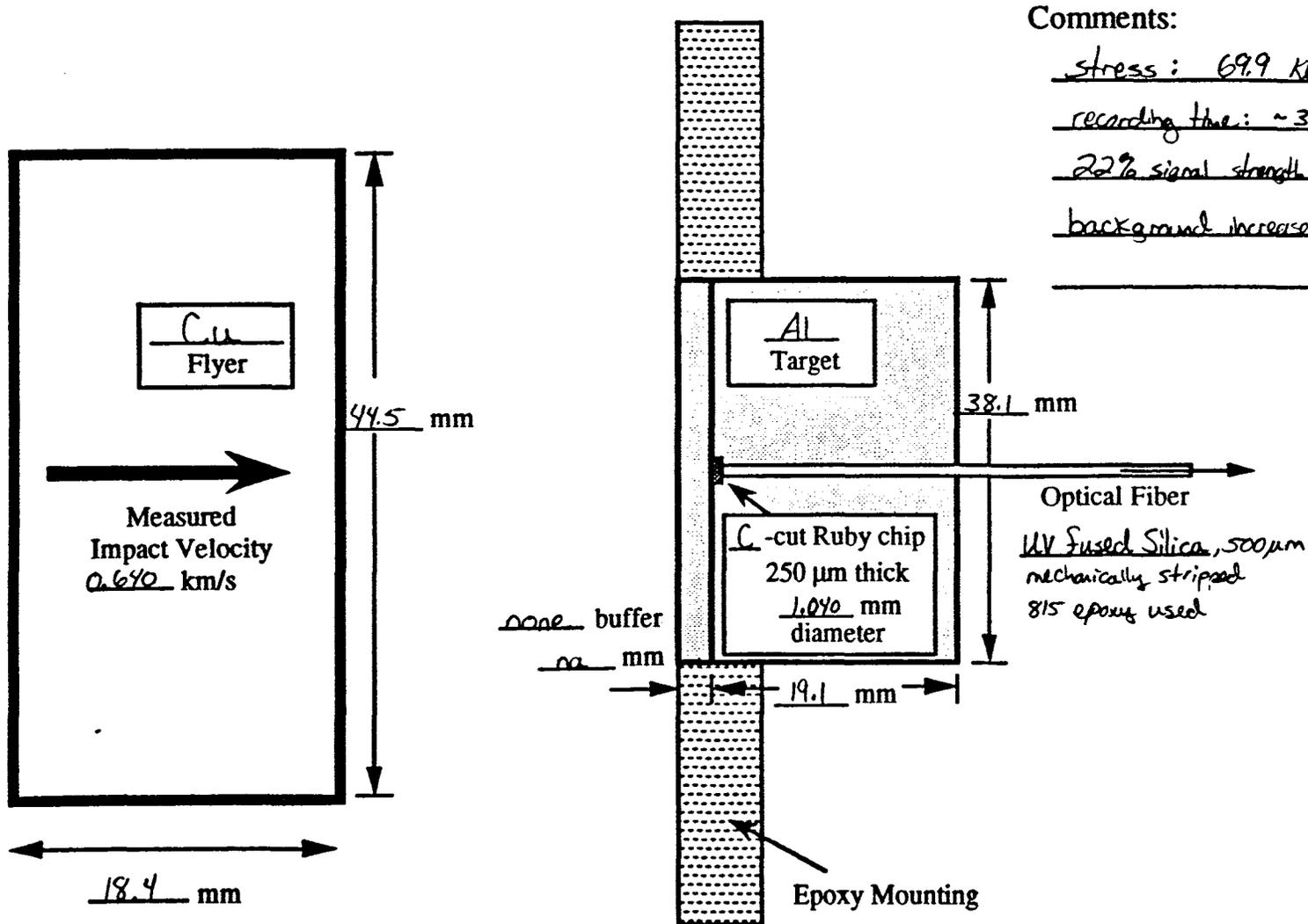|	
Experimentalist:	Kurt Zimmerman
Type of Experiment:	Uniaxial Strain, Direct Coupling
Stress:	68.7 kbar
R-Line Duration:	~3.0 µs
Post Shock Intensity:	22% signal strength
Time/Track:	100 ns
Impact Velocity:	0.640 mm/µs
Ruby Orientation:	C-cut
Ruby Dimensions:	1.04 mm diameter x 0.250 mm thick
method of manufacture:	Impact Grinder
Optical Fiber:	
material/diameter:	UV Fused Silica / 500 µm
method of stripping:	mechanical
epoxy used for bond:	815 Epoxy
Target Material:	Al
Target Dimensions:	38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness:	none
polished (y/n):	na
Impactor Material:	Cu
Impactor Dimensions:	44.5 mm diameter x 18.4 mm thick

Remarks:

This shot appears to have had an assembly problem at the ruby fiber interface due to the very large uniform background increase at impact. The signal was very "dirty" throughout the duration of the experiment with the two peaks often not discernible. A large background increase is seen at ~3.3 µs after impact and the signal totally disappears. (The muzzle vacuum was around 123 mtorr when the shot was fired - this may be the cause of the very large number of counts at impact.)

Experimental Configuration for the Ruby Chip Sensor
Shot No. _93-518_
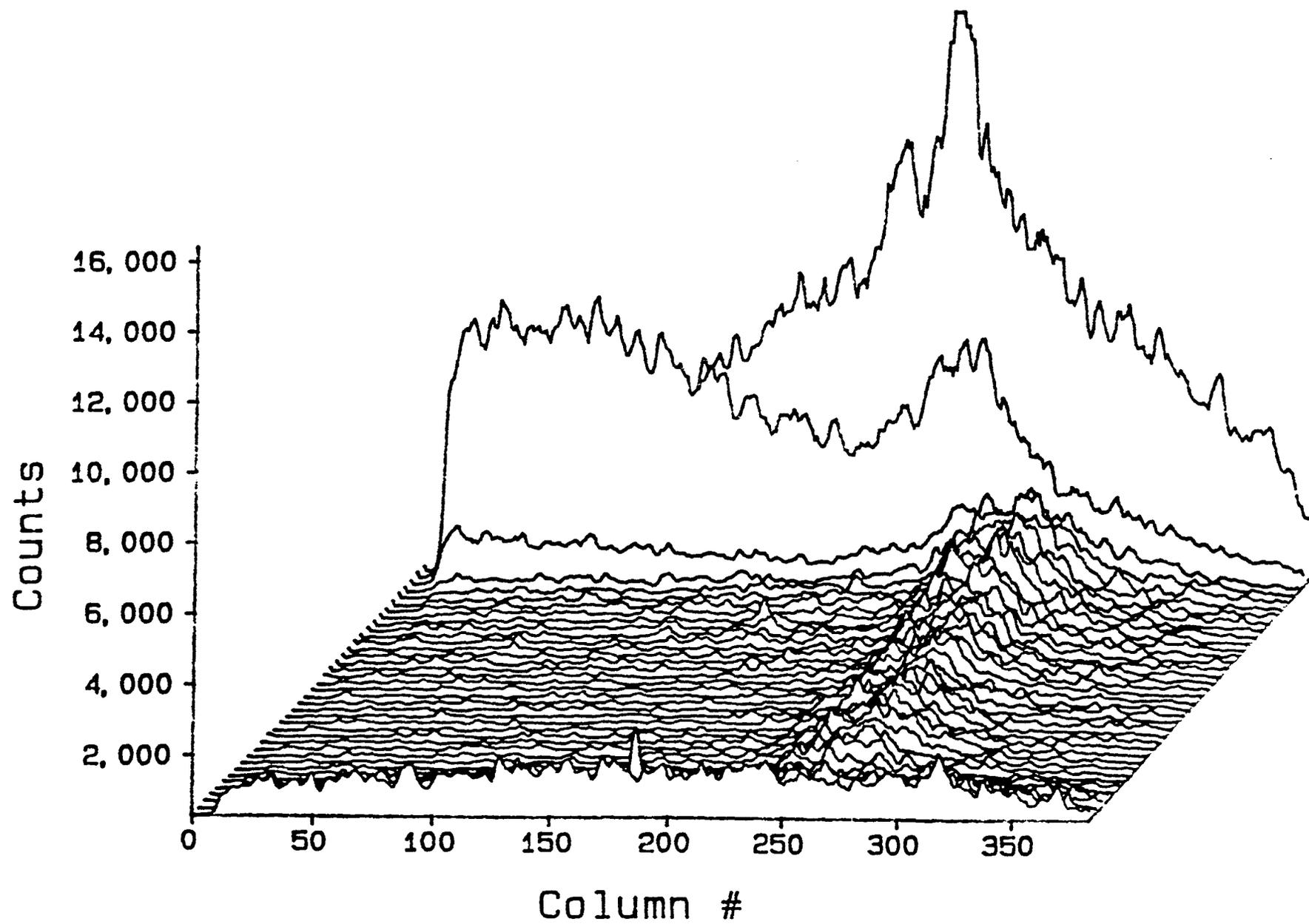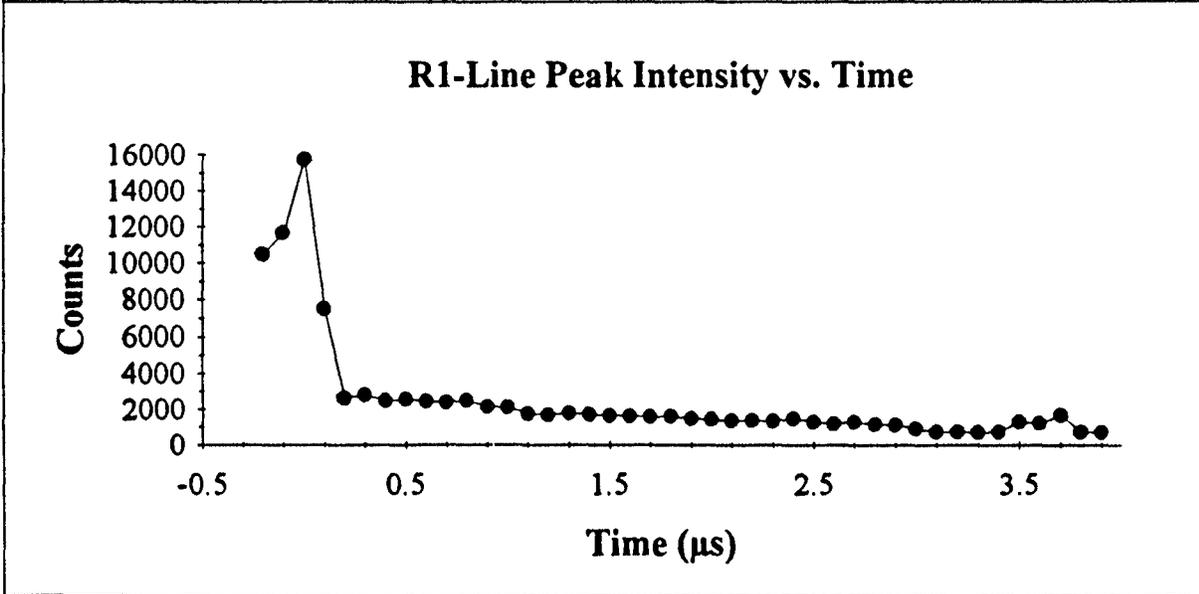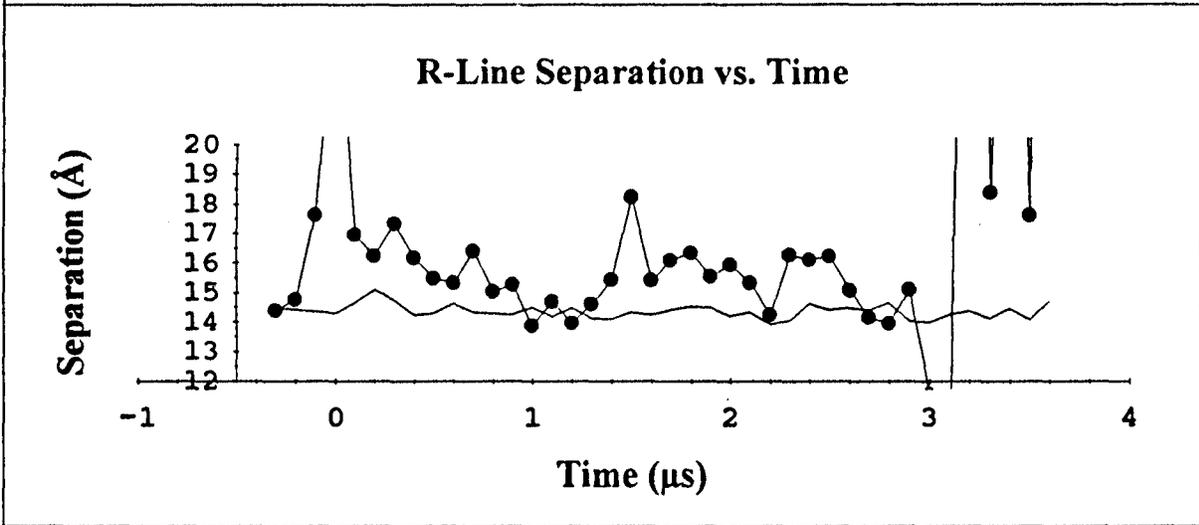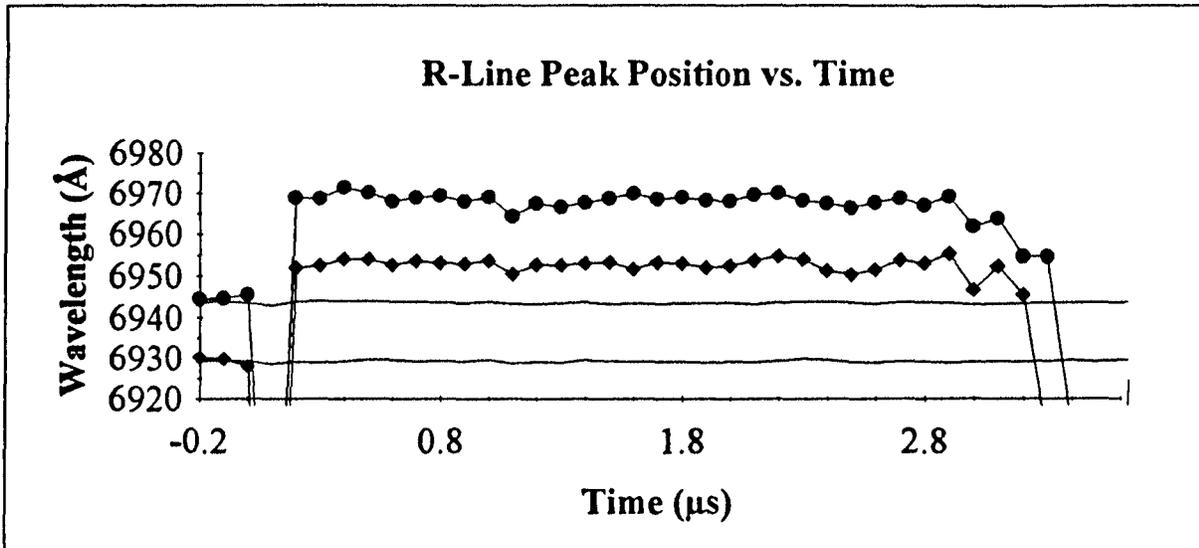
Comments:

stress : 69.9 Kbar

recording time : ~3.00 µs

22% signal strength post impact

background increase seen after 33 µs

_Cu_
Flyer

**Measured
Impact Velocity
_0.640_ km/s**

_44.5_ mm

_18.4_ mm

_Al_
Target

_38.1_ mm

Optical Fiber

_UV Fused Silica, 500 µm
mechanically stripped
815 epoxy used_

_C_ **-cut Ruby chip
250 µm thick
_1.040_ mm
diameter**

none buffer

_0_ mm

_19.1_ mm

Epoxy Mounting

L Mem: 1, Trk: 13, C: 227, X: 227, Magnitude: 760

R-Line Peak Position vs. Time

R-Line Separation vs. Time

R1-Line Peak Intensity vs. Time

Appendix C

Detailed experimental results: Uniaxial Strain Experiments

C1: 93522

C2: 93528

C3: 93535

C4: 93539

C5: 93530

C6: 93536

C7: 93537

C8: 93532

Date: 7/26/93

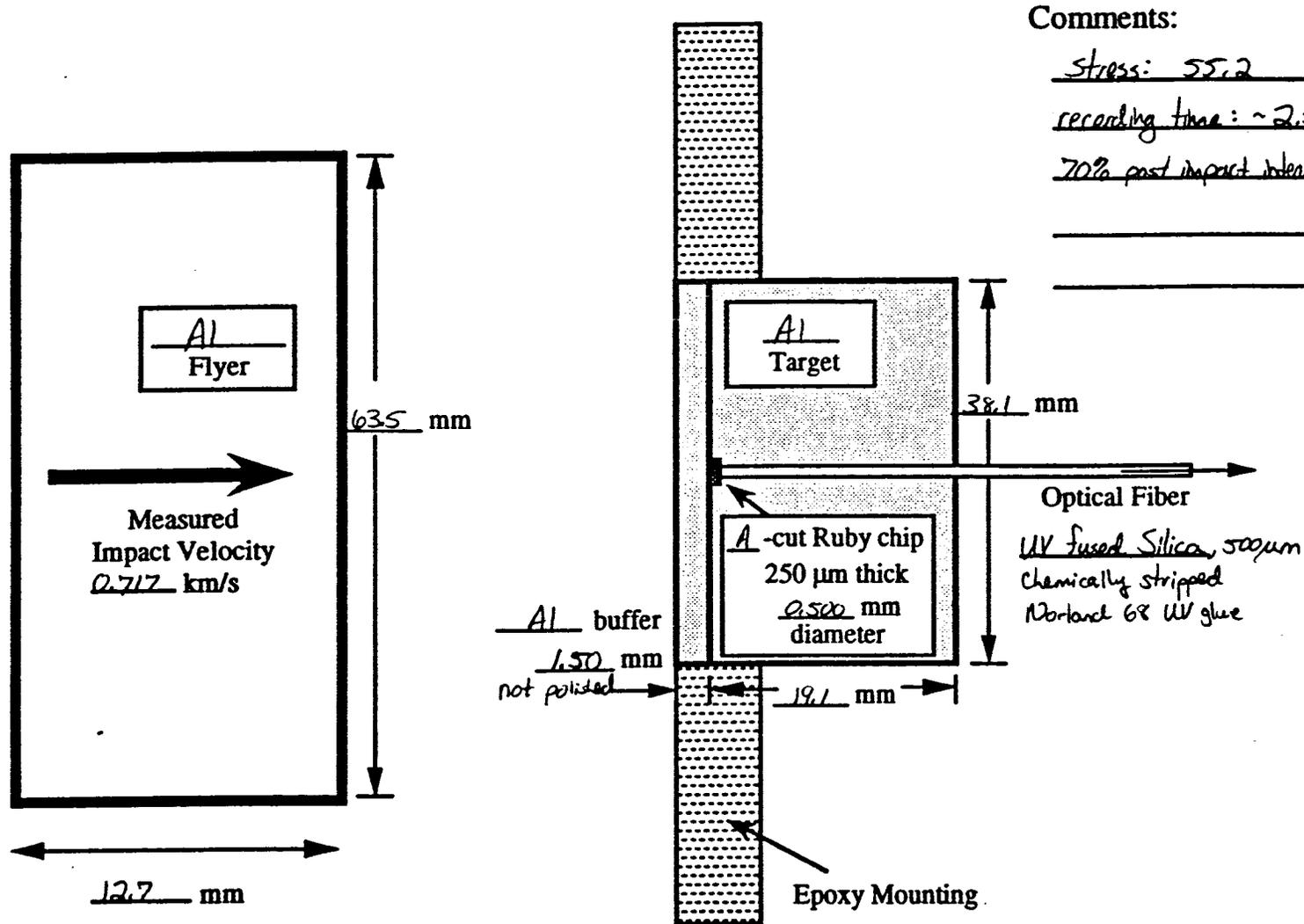Shot No.   93-522

Experimental Configuration and Specifications:

Experimentalist:	Kurt Zimmerman
Type of Experiment:	Uniaxial Strain, Direct Coupling
Stress:	54.9 kbar
R-Line Duration:	~2.55 µs
Post Shock Intensity:	70% gradually decreasing
Time/Track:	50 ns
Impact Velocity:	0.717 mm/µs
Ruby Orientation:	A-cut
Ruby Dimensions:	0.50 mm diameter x 0.250 mm thick
method of manufacture:	Laser Ablation
Optical Fiber:	
material/diameter:	UV Fused Silica, 500 µm
method of stripping:	chemical
epoxy used for bond:	Norland Optical Adhesive #68
Target Material:	Al
Target Dimensions:	38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness:	Al / 1.50 mm
polished (y/n):	n
Impactor Material:	Al
Impactor Dimensions:	63.5 mm diameter x 12.7 mm thick

Remarks:

Best results to date. The initial shock track has only one broad peak but following this the two peaks are seen clearly throughout the duration of the experiment. I digitized at 50 ns/track in order to observe what was happening when the shock arrived so my recording time was limited to 2.55 µs. The signal was clear and still present when I stopped recording. Target was prepared by polishing both ends of the fiber and inserting one end into a Teflon jig which had a 500 µm hole drilled in it. The ruby chip was placed on the fiber tip following application of the epoxy and pushed into the 500 µm hole for alignment. Pressure was applied to the fiber for a short amount of time after which the jig was placed under a UV lamp for ~10 minutes (the UV light entered the non bonded end of the fiber to illuminate the epoxy). Following this the clamp was removed and the ruby directly illuminated. The assembly was placed in a 50°C oven overnight for final curing. This is supposed to finish curing the epoxy. Care was taken to make the walls of the hole through the target as smooth and clean as possible. The ruby chips have approximately 7° of angle to them with the average large end being ~490 µm and the small end ~430µm.
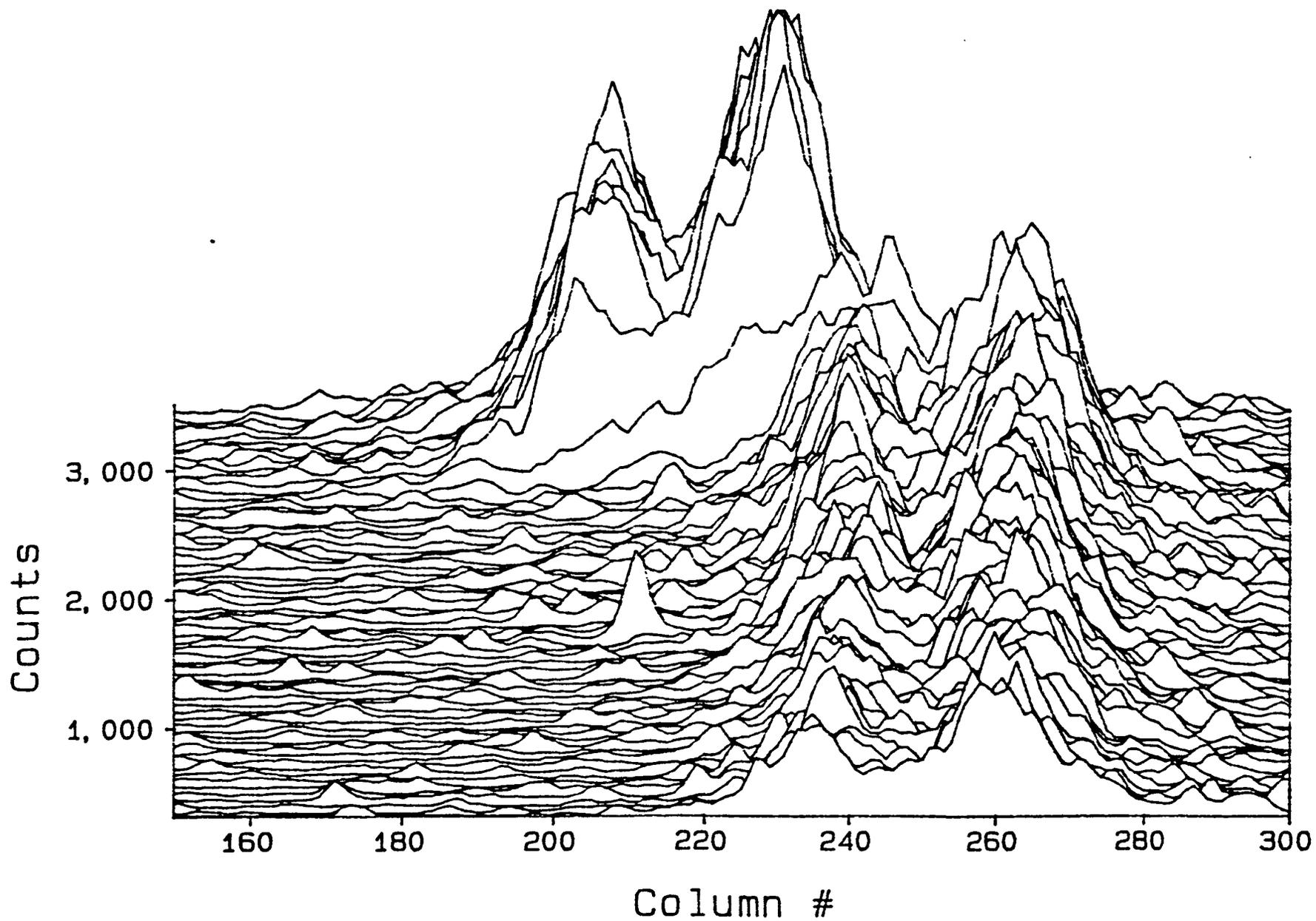
Date: 7/26/93

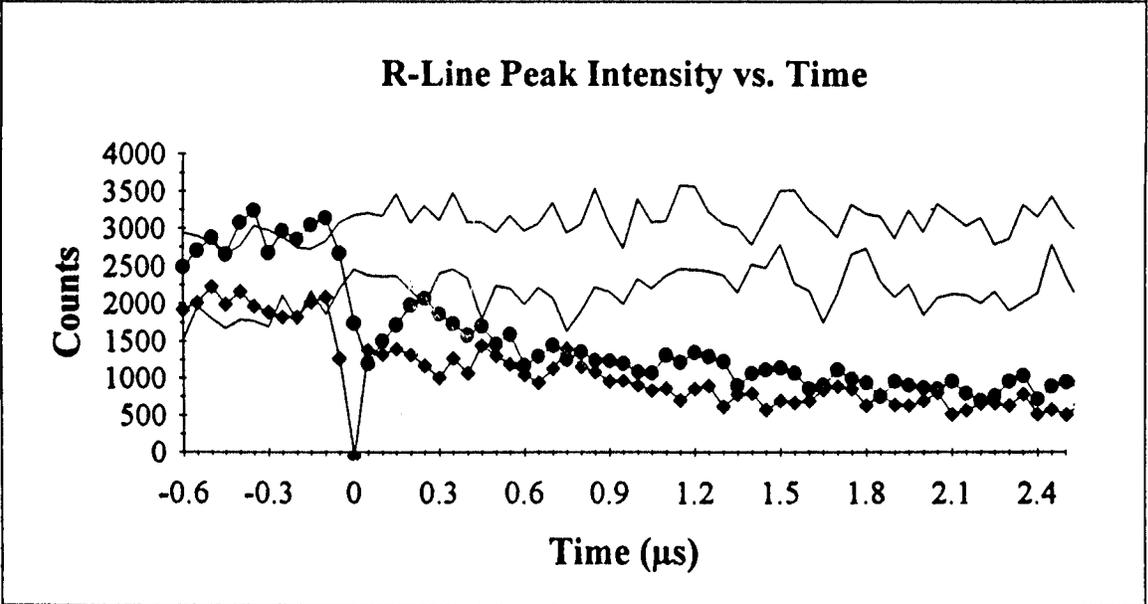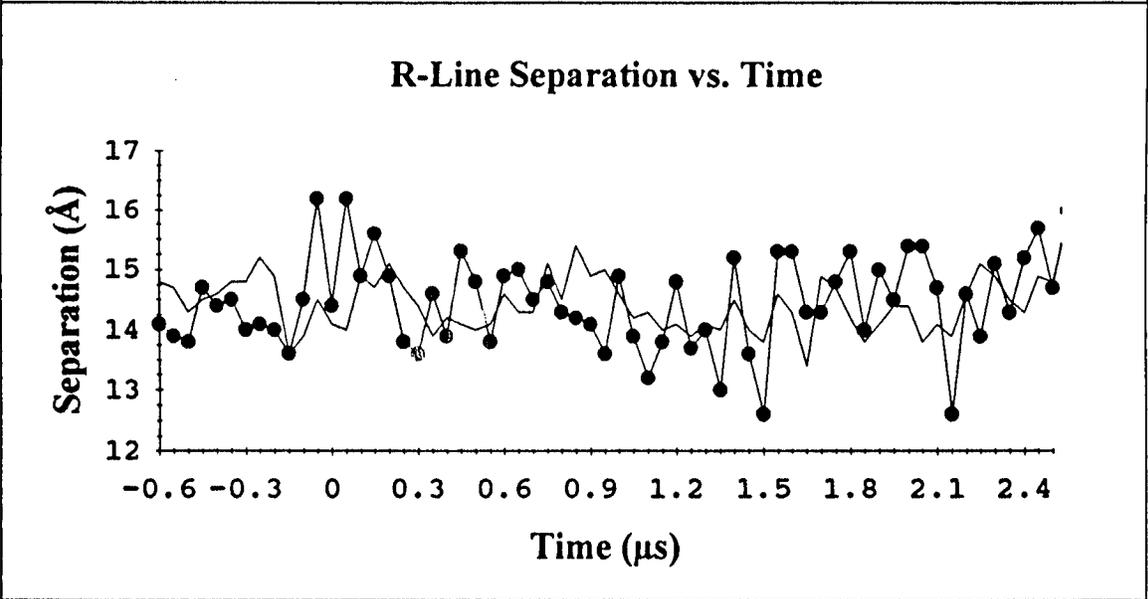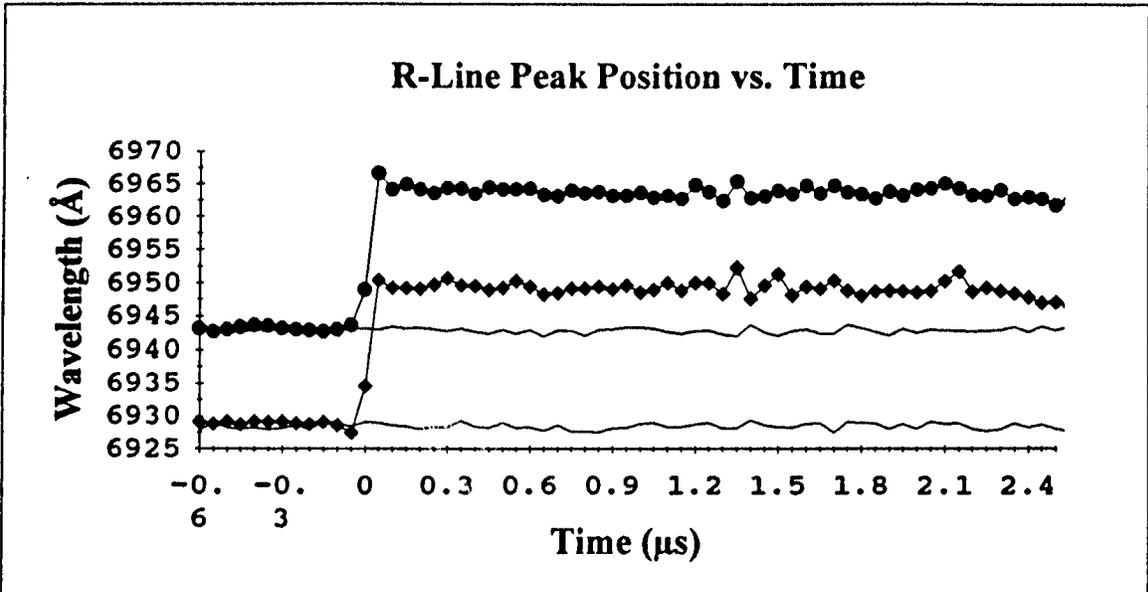# Experimental Configuration for the Ruby Chip Sensor
Shot No. 93-522

Comments:

stress: 55.2

recording time: ~2.55 µs

70% post impact intensity

_____

_____

Al
Flyer

635 mm

Measured
Impact Velocity
0.717 km/s

12.7 mm

Al
Target

38.1 mm

Optical Fiber

UV fused Silica, 500µm
Chemically stripped
Norland 68 UV glue

A -cut Ruby chip
250 µm thick
0.500 mm
diameter

Al buffer
1.50 mm
not polished

19.1 mm

Epoxy Mounting

93-522

L Mem: 1, Trk: 17, C: 265, X: 265, Magnitude: 2,641

R-Line Peak Position vs. Time

R-Line Separation vs. Time

R-Line Peak Intensity vs. Time

Date: 16 Aug 93

Shot No.   93-528

Experimental Configuration and Specifications:

Experimentalist: Dinos Constantinou
Type of Experiment: Uniaxial Strain, Direct Coupling
Stress: 55.9 kbar
R-Line Duration: 5.3 μs
Post Shock Intensity: 71 %
Time/Track: 100 ns
Impact Velocity: 0.728 mm/μs
Ruby Orientation: A-cut
Ruby Dimensions: 0.5 mm diameter x 0.250 mm thick
     method of manufacture: Laser Ablation
Optical Fiber:
     material/diameter: NIR Fused Silica 500 μm diameter
     method of stripping: mechanical
     epoxy used for bond: Norland Optical Adhesive #68
Target Material: Al
Target Dimensions: 38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness: Al / 1.50 mm
     polished (y/n):   n
Impactor Material: Al
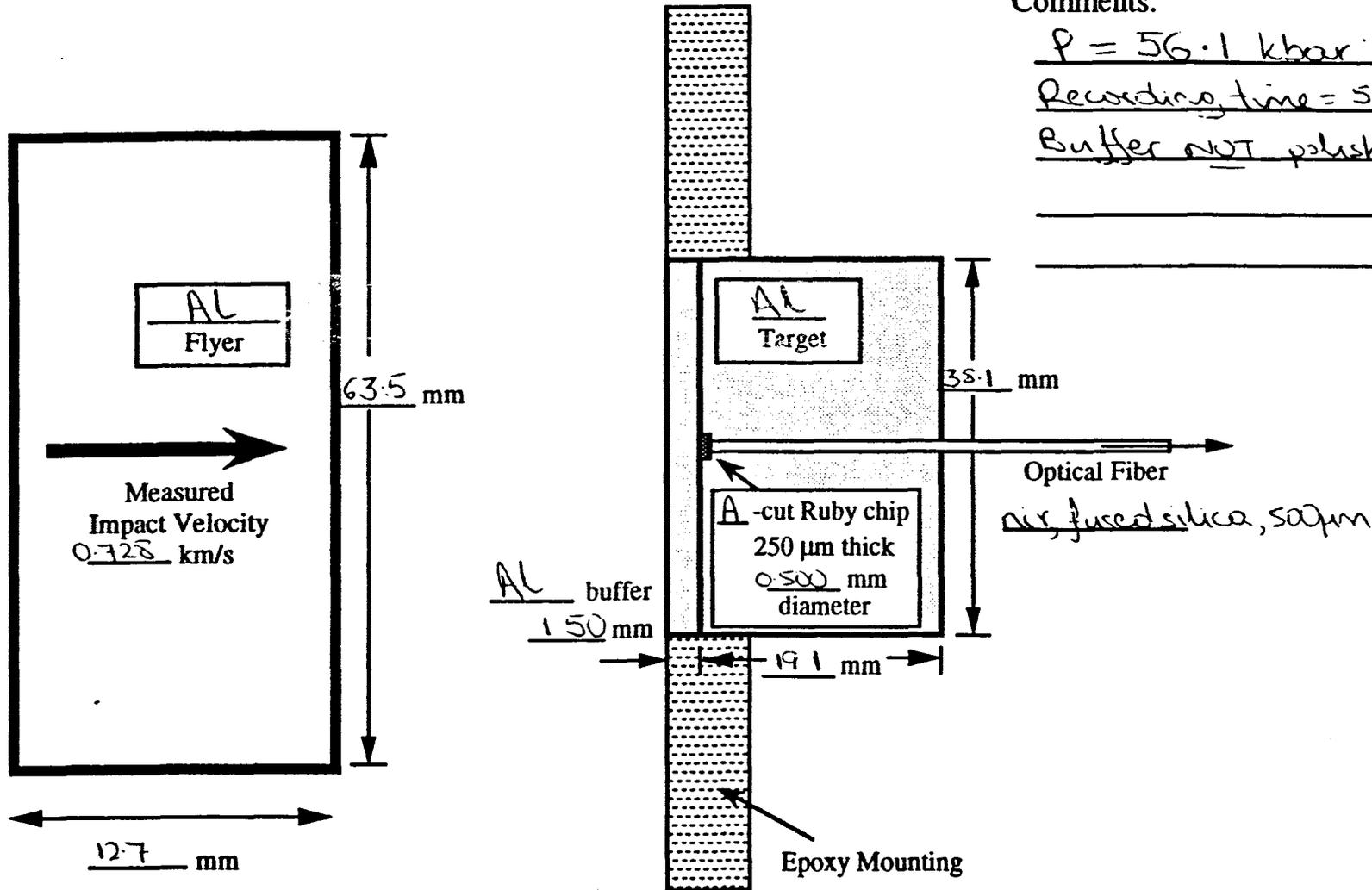Impactor Dimensions: 63.5 mm diameter x 12.7 mm thick

Remarks:

Dinos' first ruby shot. One end of the fiber was first polished; the connector at this end was set with the CrystalBond 509 adhesive of Aremco Products Inc. and subsequently removed by soaking in acetone overnight. This end of the fiber was then inserted into the teflon jig with the 500 μm hole. We made sure that it was well polished, without cracks or chips. We cleaned it carefully under the microscope and then applied as small an amount of the UV curing epoxy as possible. A cleaned human hair was then used to remove most of this epoxy and to spread the remaining into a uniform layer. The already cleaned ruby chip was then put in place with the flat surface of smaller area upwards. A slight pressure was applied on the chip using a metallic needle. The arrangement was checked under the microscope and the epoxy was then cured by exposure to UV light for 10 mins in each of the two directions. The uniformity and cleanliness of the bond were checked before the epoxy was finally cured in the oven overnight. A connector was then placed at the other end of the fiber and polished. The fiber and

chip were then inserted in a target as follows: everything was thoroughly cleaned; the fiber was cleaned along its length by carefully rubbing it in tissue paper wet with ethanol and acetone. A stripped length of optical fiber was used to insert freshly degassed 815 epoxy into the target hole, making sure the epoxy covered the whole of the internal wall. The target was then placed on a lapped flat plate and the ruby bearing fiber was inserted. The assembly was allowed to cure overnight. The target face was then carefully sanded and lapped before the buffer plate was glued on. Care was taken to obtain as thin a bond as possible by using 815 epoxy, rubbing the target and buffer plate together and pressing them overnight. The target was then set in the target ring while the latter was clamped onto a flat plate, thus ensuring that the fiber was going to be impacted in a direction parallel to its length as far as possible. The target was sanded and lapped once it was set in the target ring and before shooting. Good quality spectra were obtained.

Date: _ Aug 93

Experimental Configuration for the Ruby Chip Sensor
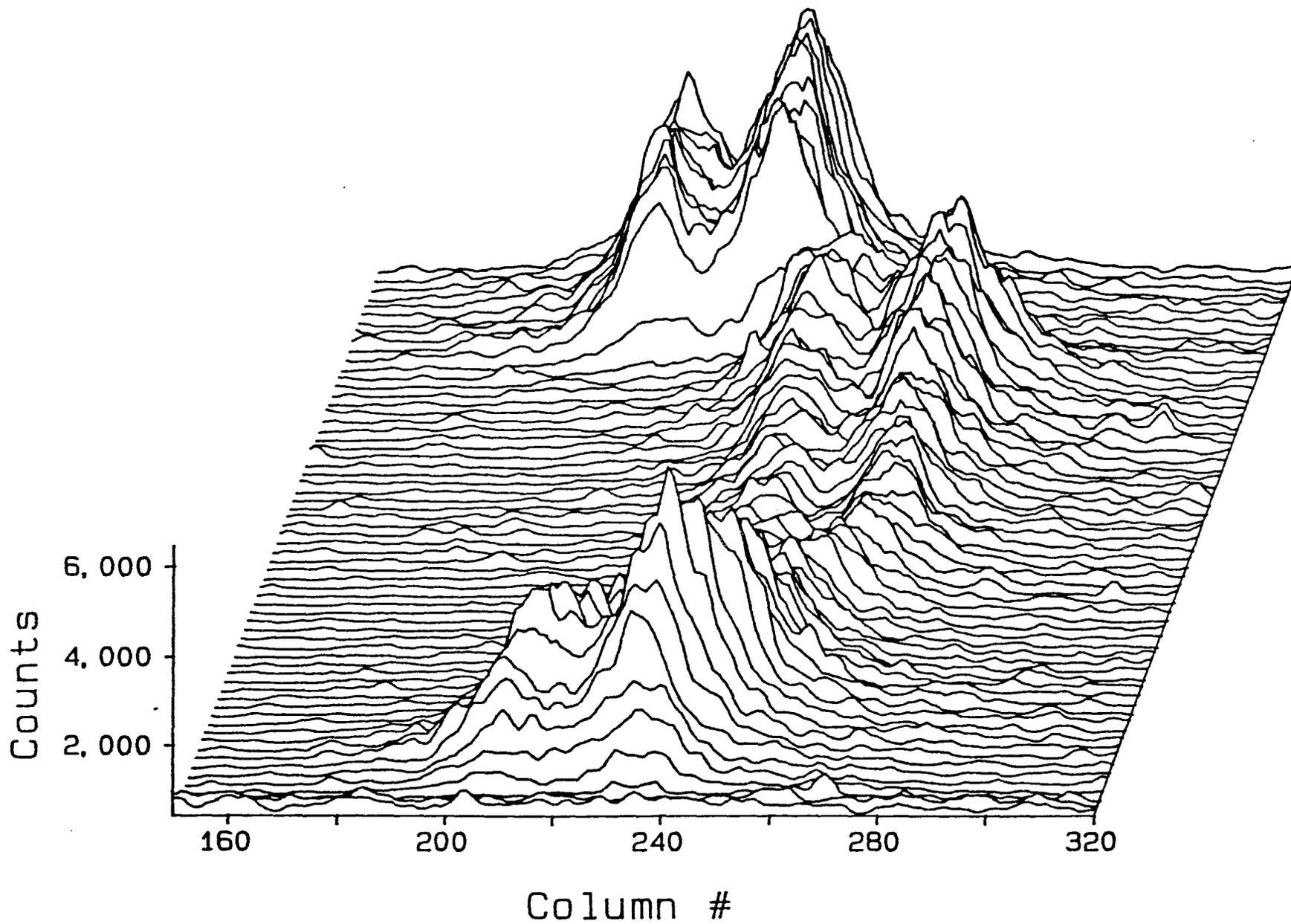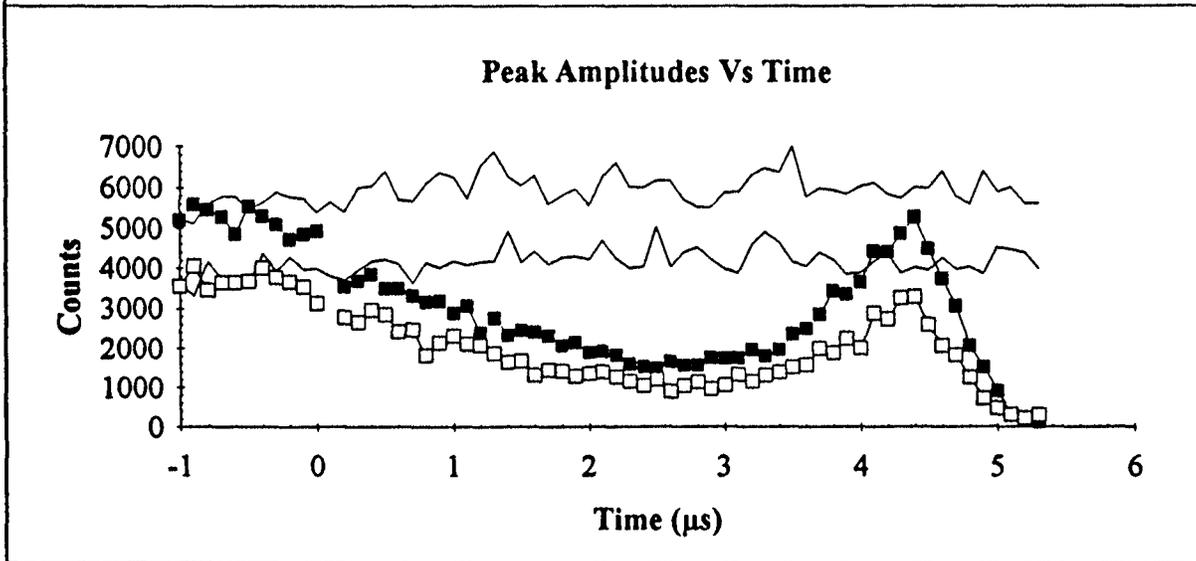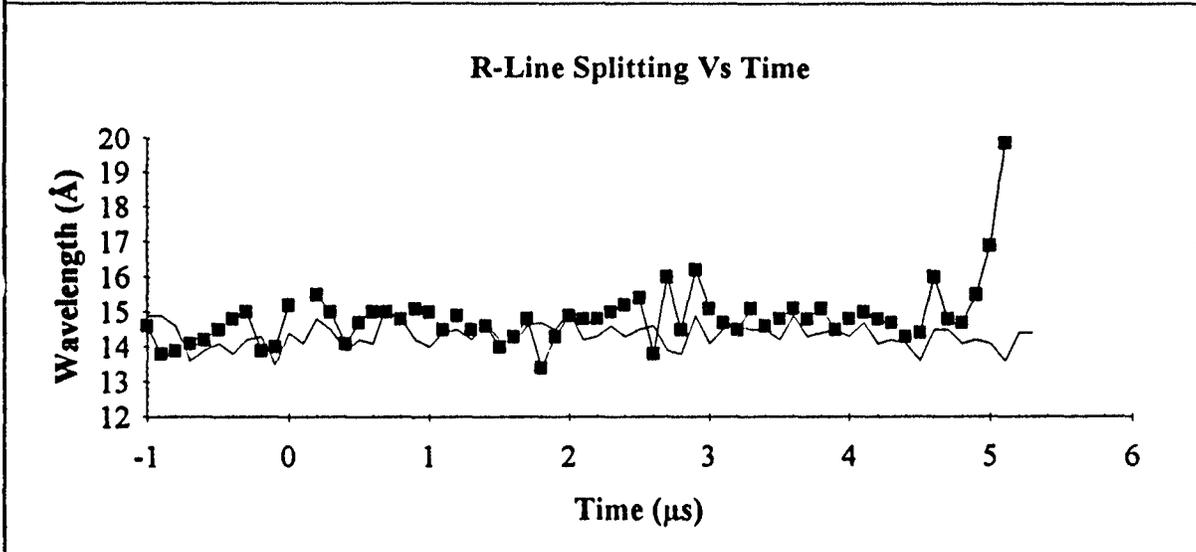## Shot No. 93-528

AL
Flyer

Measured
Impact Velocity
0.728 km/s

63.5 mm

12.7 mm

AL
Target

38.1 mm

Optical Fiber

air, fused silica, 500μm

A -cut Ruby chip
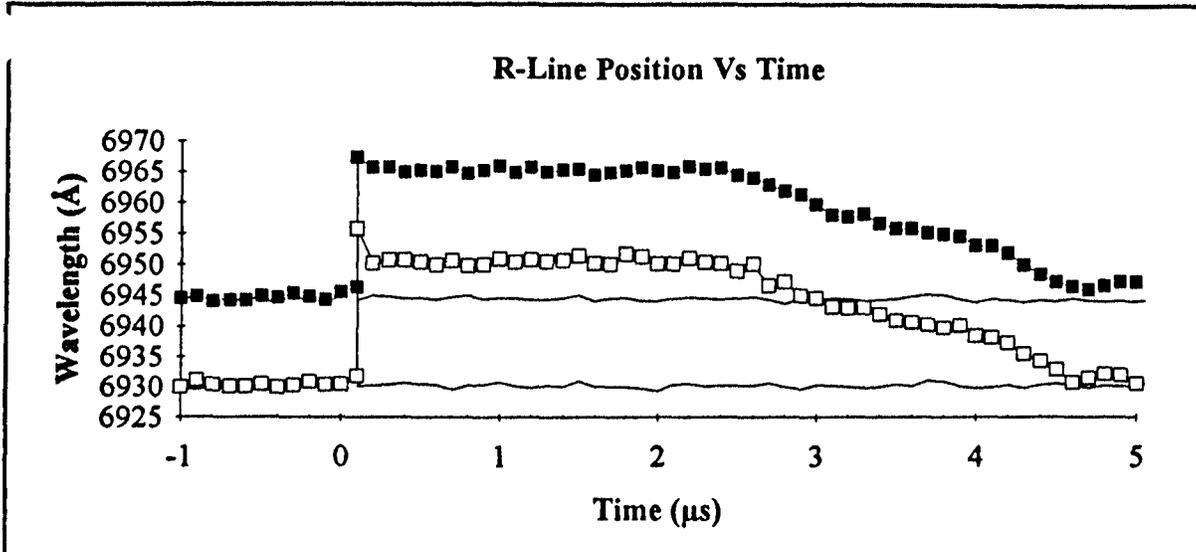250 μm thick
0.500 mm
diameter

AL buffer
1.50 mm

19.1 mm

Epoxy Mounting

Comments:
P = 56.1 kbar
Recording time = 5.3 μs
Buffer NOT polished!

0: SHOT.DAT Mem: 1, Trk: 1, C: 0, X: 0, Magnitude: 292

R-Line Position Vs Time

Wavelength (Å)

Time (μs)

R-Line Splitting Vs Time

Wavelength (Å)

Time (μs)

Peak Amplitudes Vs Time

Counts

Time (μs)

Date: 15 Sept 93

Shot No.   93-535

Experimental Configuration and Specifications:

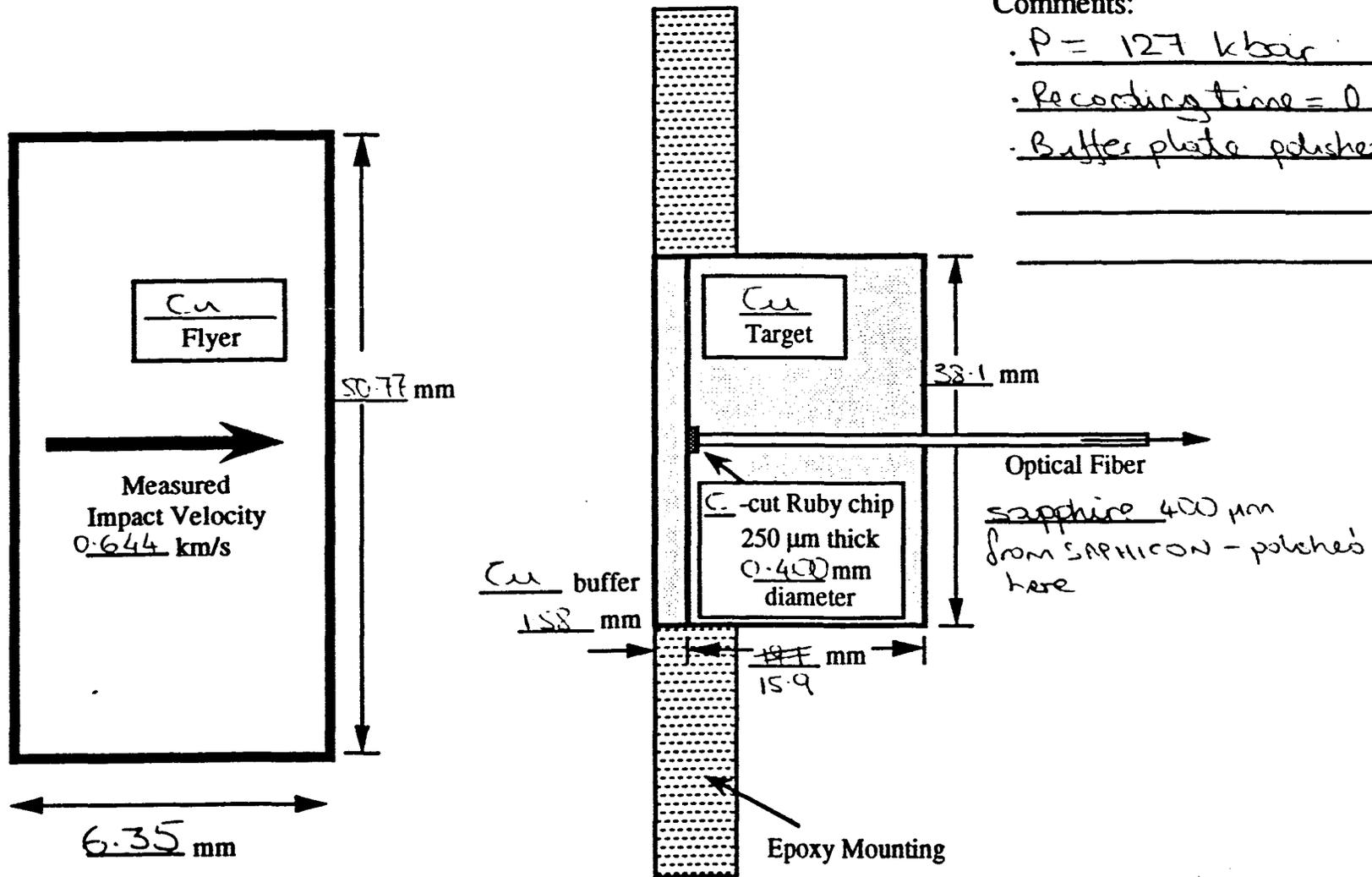|	
Experimentalist:	Dinos Constantinou / Kurt Zimmerman
Type of Experiment:	Uniaxial Strain, Direct Coupling
Stress:	120.5 kbar
R-Line Duration:	0 μs
Post Shock Intensity:	0 %
Time/Track:	100 ns
Impact Velocity:	0.644 mm/μs
Ruby Orientation:	C-cut
Ruby Dimensions:	0.4 mm diameter x 0.250 mm thick
method of manufacture:	Laser Ablation
Optical Fiber:	
material/diameter:	Sapphire (w/o cladding) 400 μm diameter
method of stripping:	mechanical
epoxy used for bond:	Norland Optical Adhesive #68
Target Material:	Cu
Target Dimensions:	38.1 mm diameter x 15.9 mm thick
Buffer Material/Thickness:	Cu / 1.58 mm
polished (y/n):	y
Impactor Material:	Cu
Impactor Dimensions:	50.77 mm diameter x 6.35 mm thick

Remarks:

Shot prepared by Kurt and fired by Dinos. The sapphire fiber was polished here using diamond paste from Buehler. There were doubts about the flatness of the fiber tip that the ruby was glued to. The same tip was also chipped at the edges.When the shock arrives at the ruby the signal is lost; the only signal observed from then on is the weak impurity luminescence from the fiber itself.
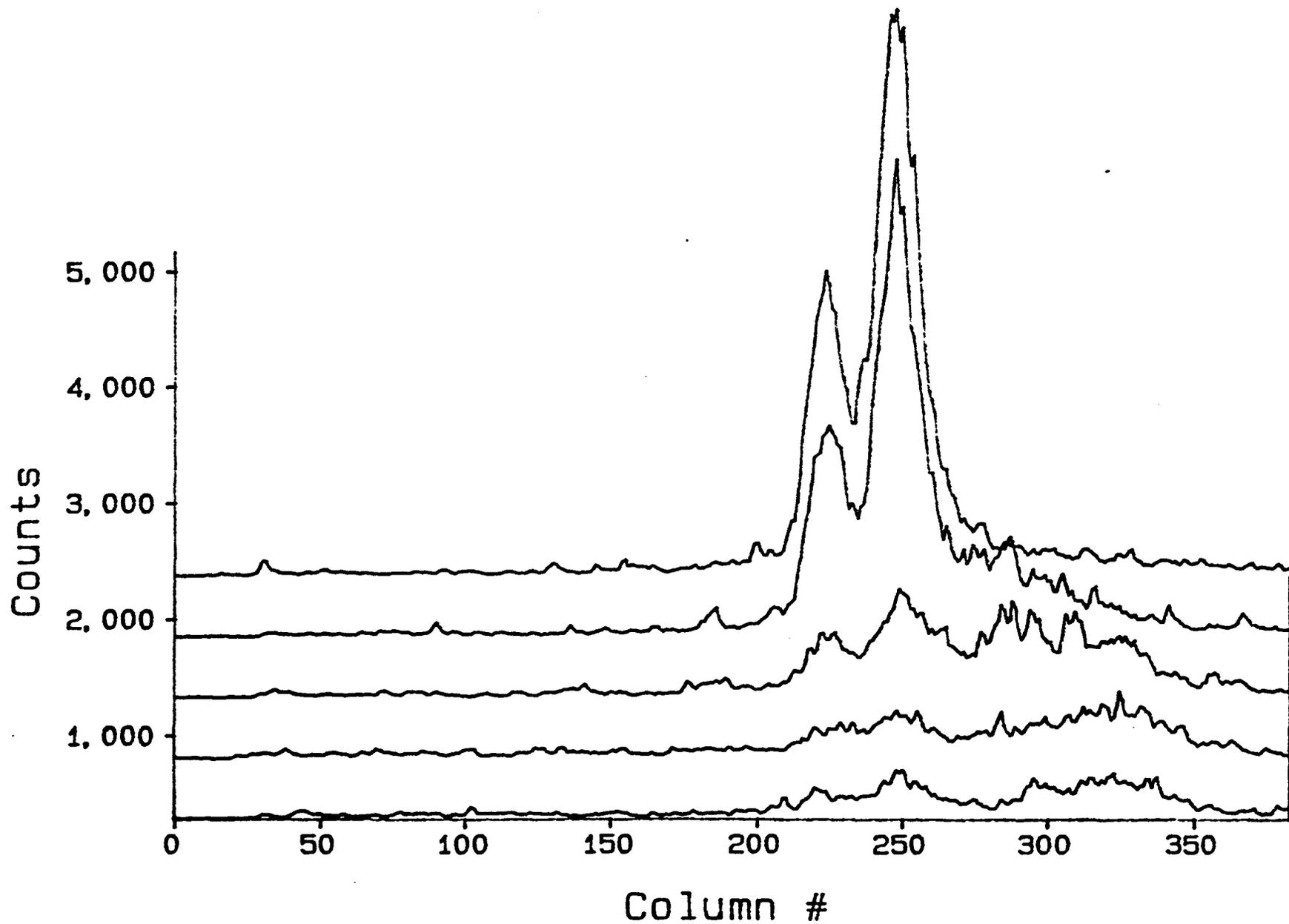
Experimental Configuration for the Ruby Chip Sensor
Shot No. 93-535

Comments:

- P = 127 kbar
- Recording time = 0
- Buffer plate polished

Cu
Flyer

50.77 mm

Measured
Impact Velocity
0.644 km/s

6.35 mm

Cu
Target

38.1 mm

Optical Fiber

sapphire 400 μm
from SAPHICON – polished here

C -cut Ruby chip
250 μm thick
0.400 mm
diameter

Cu buffer
1.58 mm

19.1 mm
15.9

Epoxy Mounting

93·5?

0: SHOT.DAT Mem: 1, Trk: 1, C: 0, X: 0, Magnitude: 294

SHOT 93535 16Sept93 TRACKS 5-1

Date: 10/12/93

Shot No.   93-539

Experimental Configuration and Specifications:

Experimentalist: Kurt Zimmerman
Type of Experiment: Uniaxial Strain, Direct Coupling
Stress: 86.5 kbar
R-Line Duration: ~1.4 µs
Post Shock Intensity: 30% steady decrease
Time/Track: 100 ns
Impact Velocity: 0.492 mm/µs
Ruby Orientation: C-cut
Ruby Dimensions: 0.4 mm diameter x 0.250 mm thick
    method of manufacture: Laser Ablation
Optical Fiber:
    material/diameter: Sapphire (w/o cladding) / 422 µm
    method of stripping: na
    epoxy used for bond: Norland Optical Adhesive #68
Target Material: Cu
Target Dimensions: 38.1 mm diameter x 15.9 mm thick
Buffer Material/Thickness: Cu / 1.5 mm
    polished (y/n):   y
Impactor Material: Cu
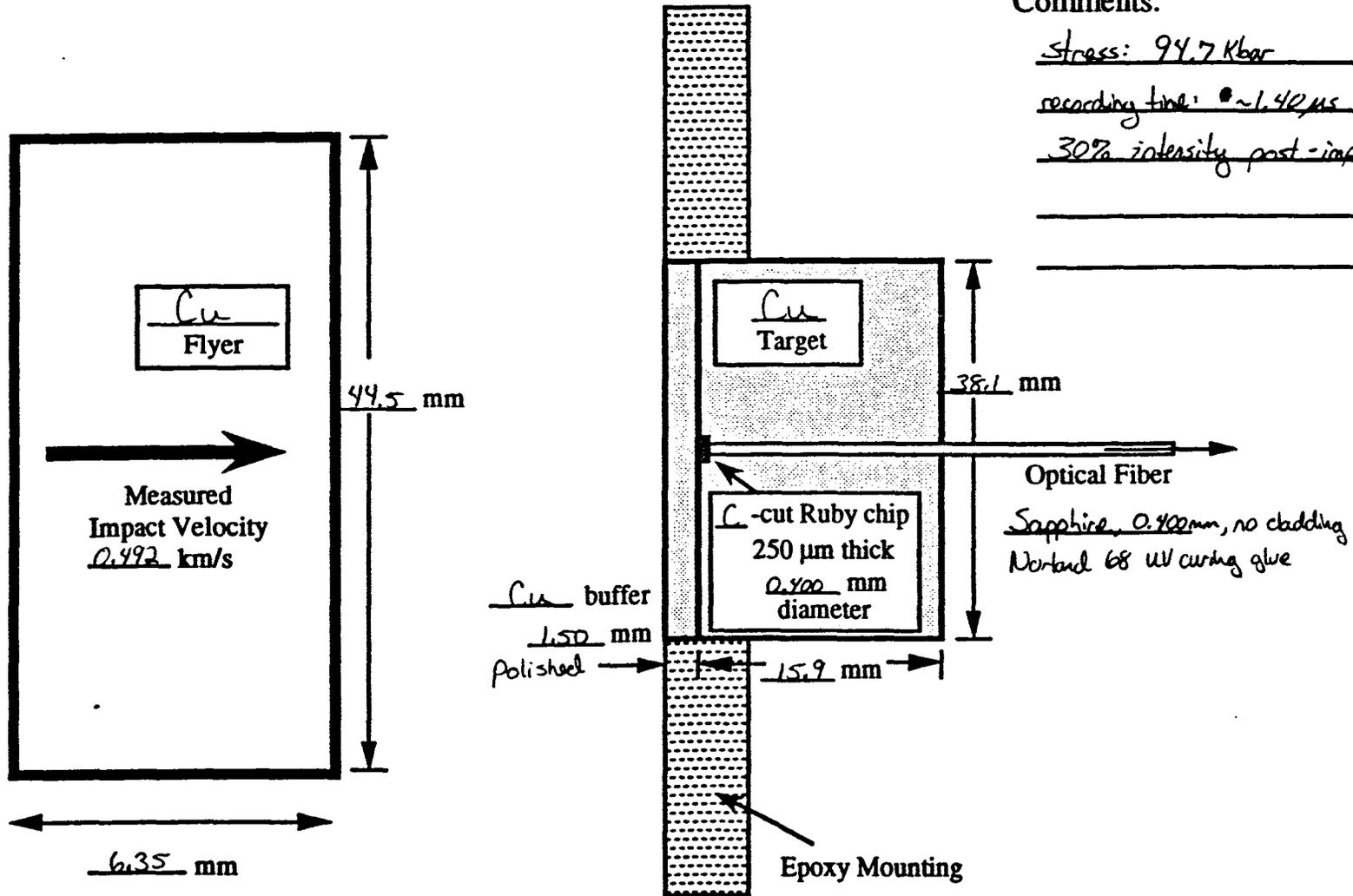Impactor Dimensions: 44.5 mm diameter x 6.35 mm thick

Remarks:

The data is somewhat noisy but the two peaks are observable. Impact occurred early due to a 5% error in the velocity. There are residual R-line peaks due to impurities in the sapphire fiber; however, they amount to only a small fraction of the counts seen from the ruby. This shot was the first using the polished sapphire optical fiber furnished by Saphikon. It has a wavy surface but still guides fairly well. There is no cladding on the fiber, the epoxy surrounding the fiber will act as the cladding. In this shot the hole in the copper was about 5 µm too small to accommodate the sapphire fiber. In the end I forced the fiber through and it cut out the copper necessary for it to fit. In the future we will want to make sure the hole is larger than the fiber to accommodate an epoxy cladding. The target was assembled similar to the previous shots in all other aspects. There was no background increase observed over the duration of the experiment.
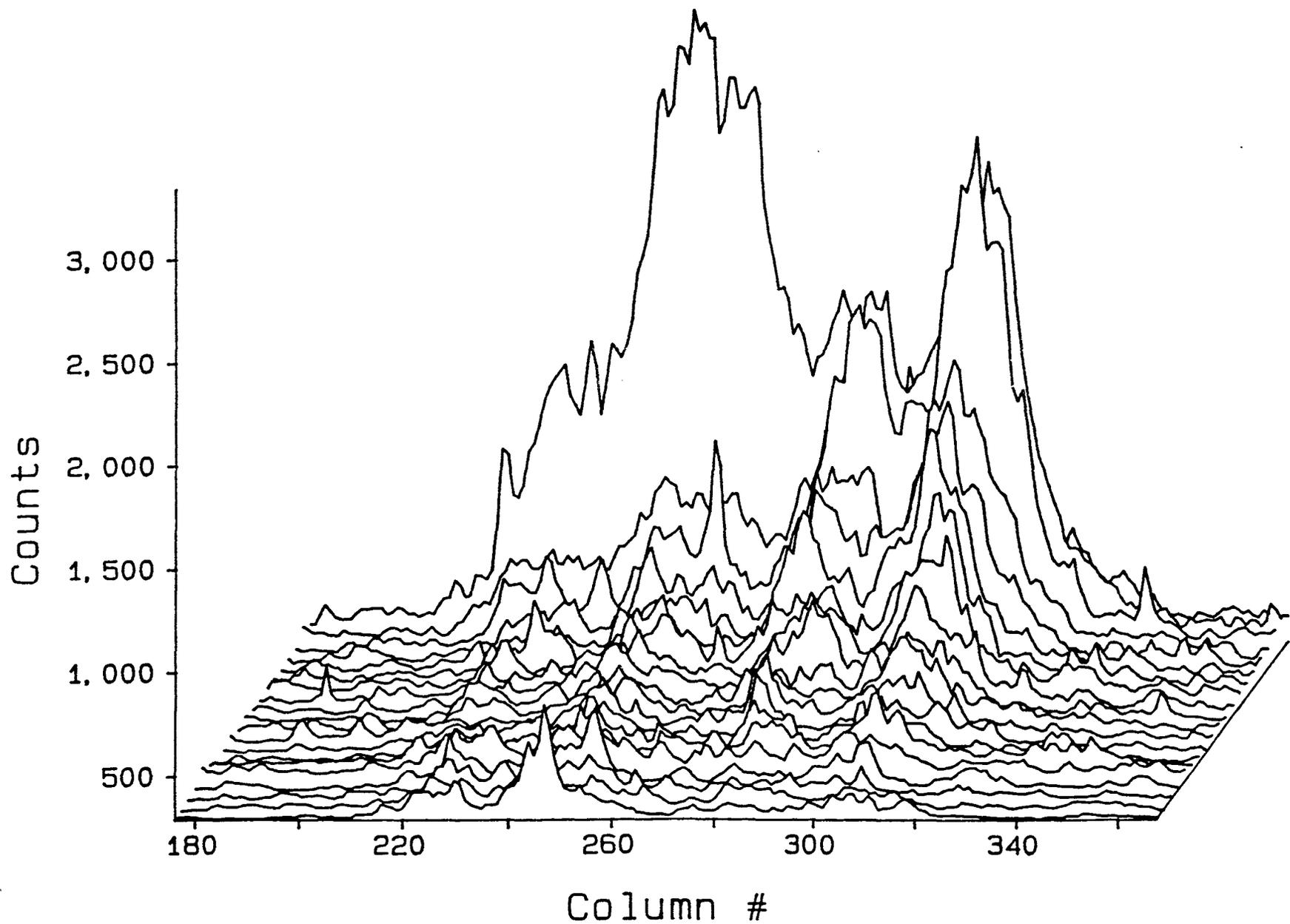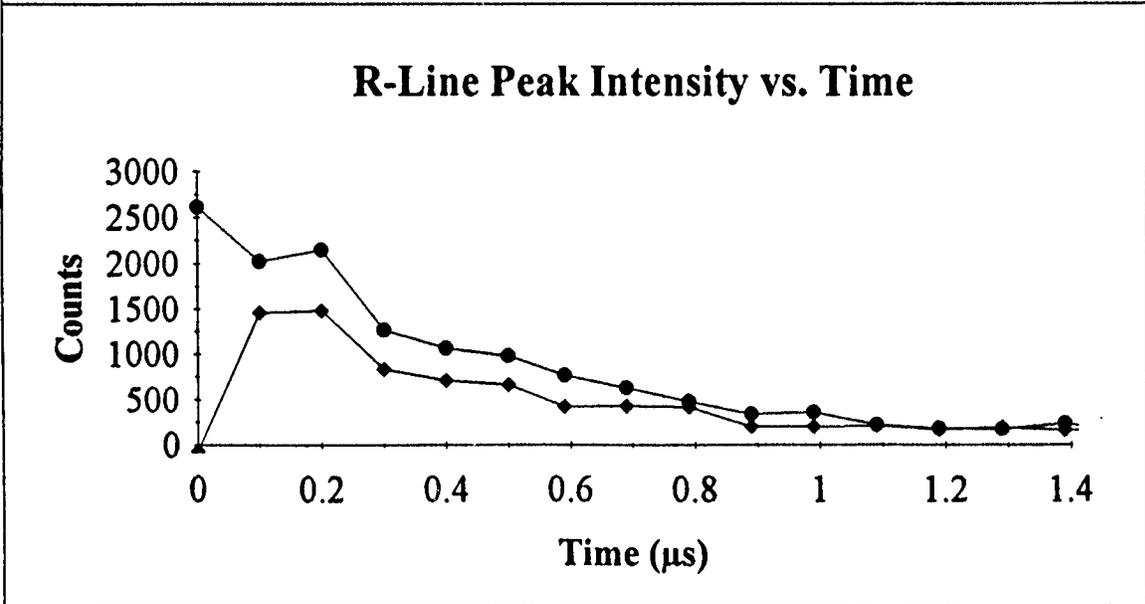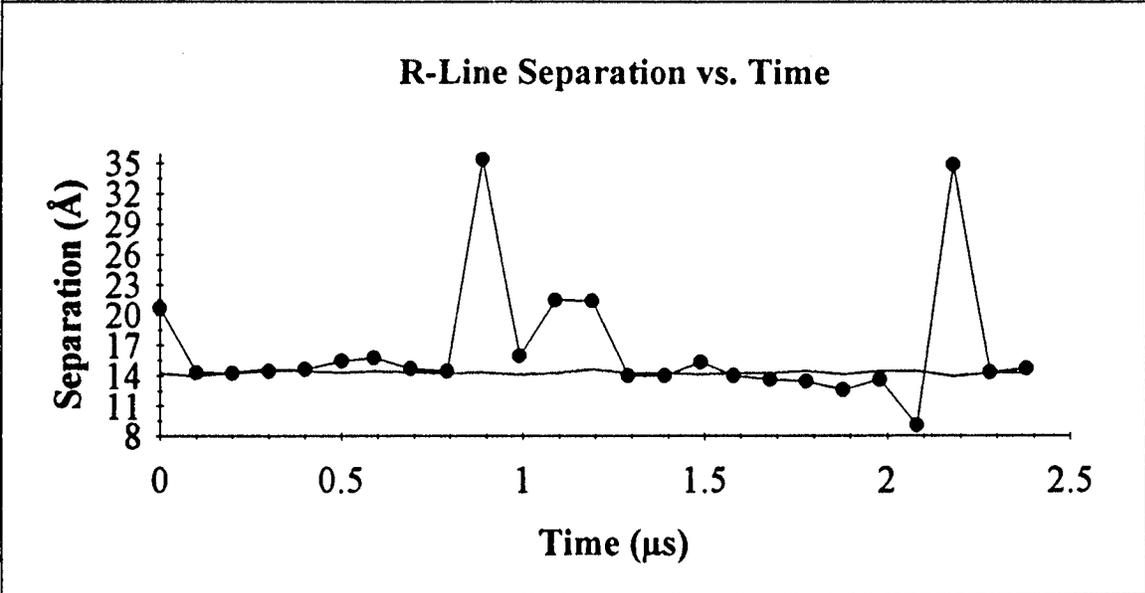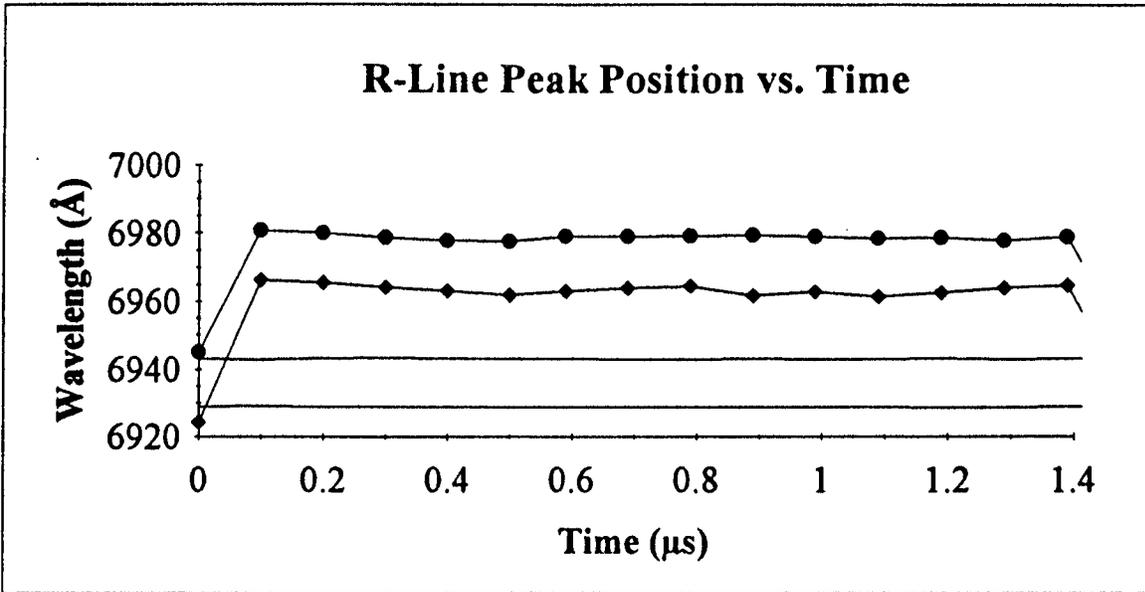
Date: 10/12/93

Experimental Configuration for the Ruby Chip Sensor
Shot No. 93-539

Cu
Flyer

44.5 mm

Measured
Impact Velocity
0.492 km/s

6.35 mm

Cu
Target

38.1 mm

Cu buffer

1.50 mm

Polished

Optical Fiber

C -cut Ruby chip
250 µm thick
0.400 mm
diameter

15.9 mm

Epoxy Mounting

O: SHOT.DAT Mem: 1, Trk: 3, C: 272, X: 272, Magnitude: 842

R-Line Peak Position vs. Time

R-Line Separation vs. Time

R-Line Peak Intensity vs. Time

Date: 18 Aug 93

Shot No.   93-530

Experimental Configuration and Specifications:

Experimentalist: Dinos Constantinou
Type of Experiment: Uniaxial Strain, Direct Coupling
Stress: 67.1 kbar
R-Line Duration: 6 μs
Post Shock Intensity: 62 %
Time/Track: 100 ns
Impact Velocity: 0.628 mm/μs
Ruby Orientation: A-cut
Ruby Dimensions: 0.5 mm diameter x 0.250 mm thick
    method of manufacture: Laser Ablation
Optical Fiber:
    material/diameter: NIR Fused Silica 500 μm diameter
    method of stripping: mechanical
    epoxy used for bond: Norland Optical Adhesive #68
Target Material: Al
Target Dimensions: 38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness: Al / 1.47 mm
    polished (y/n):   y
Impactor Material: Cu
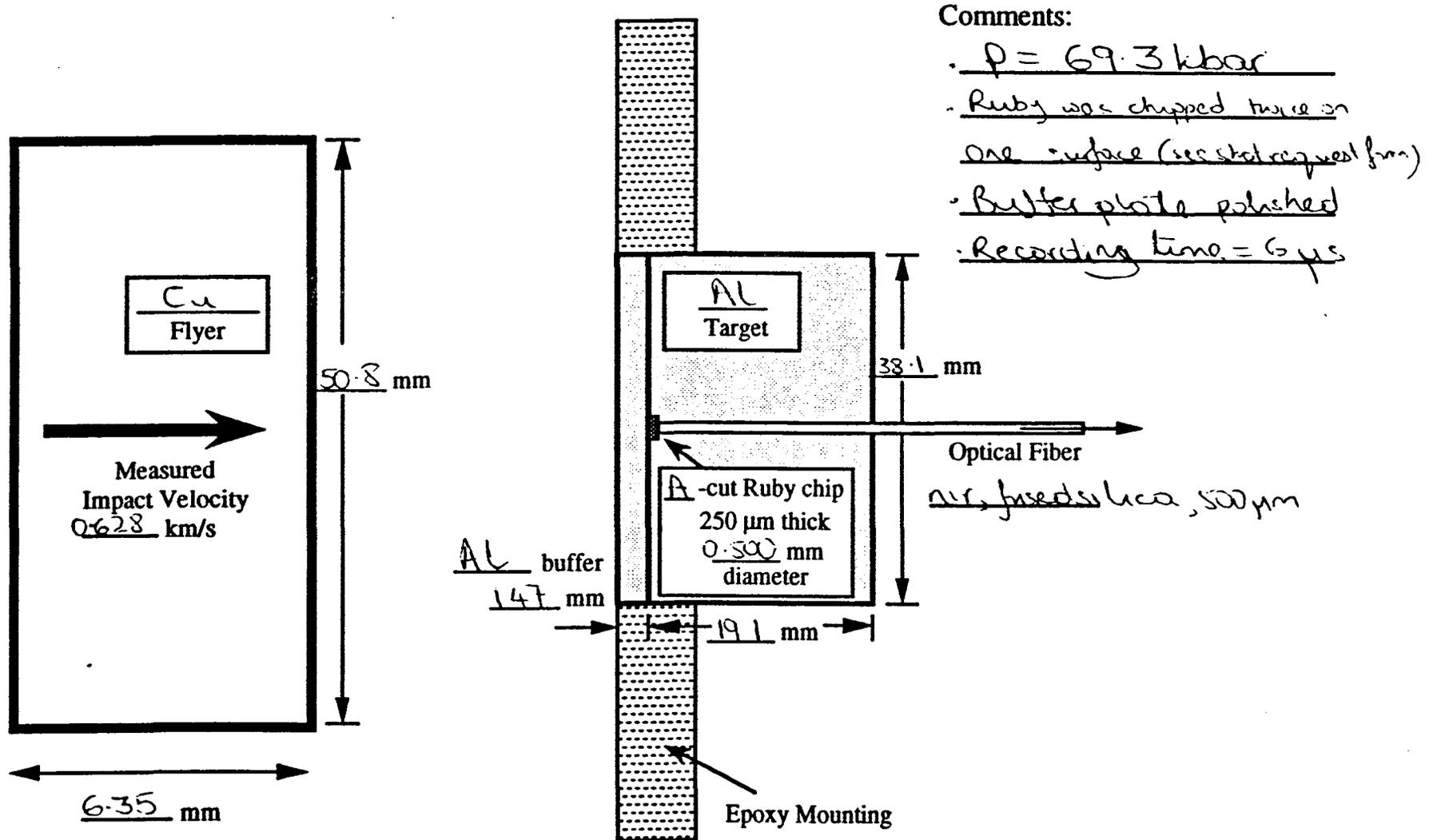Impactor Dimensions: 50.8 mm diameter x 6.35 mm thick

Remarks:

Preparation as in shot #93-528. The ruby chip used was of substandard quality: it had two chips on the edges of the surface of larger area. Good quality spectra.
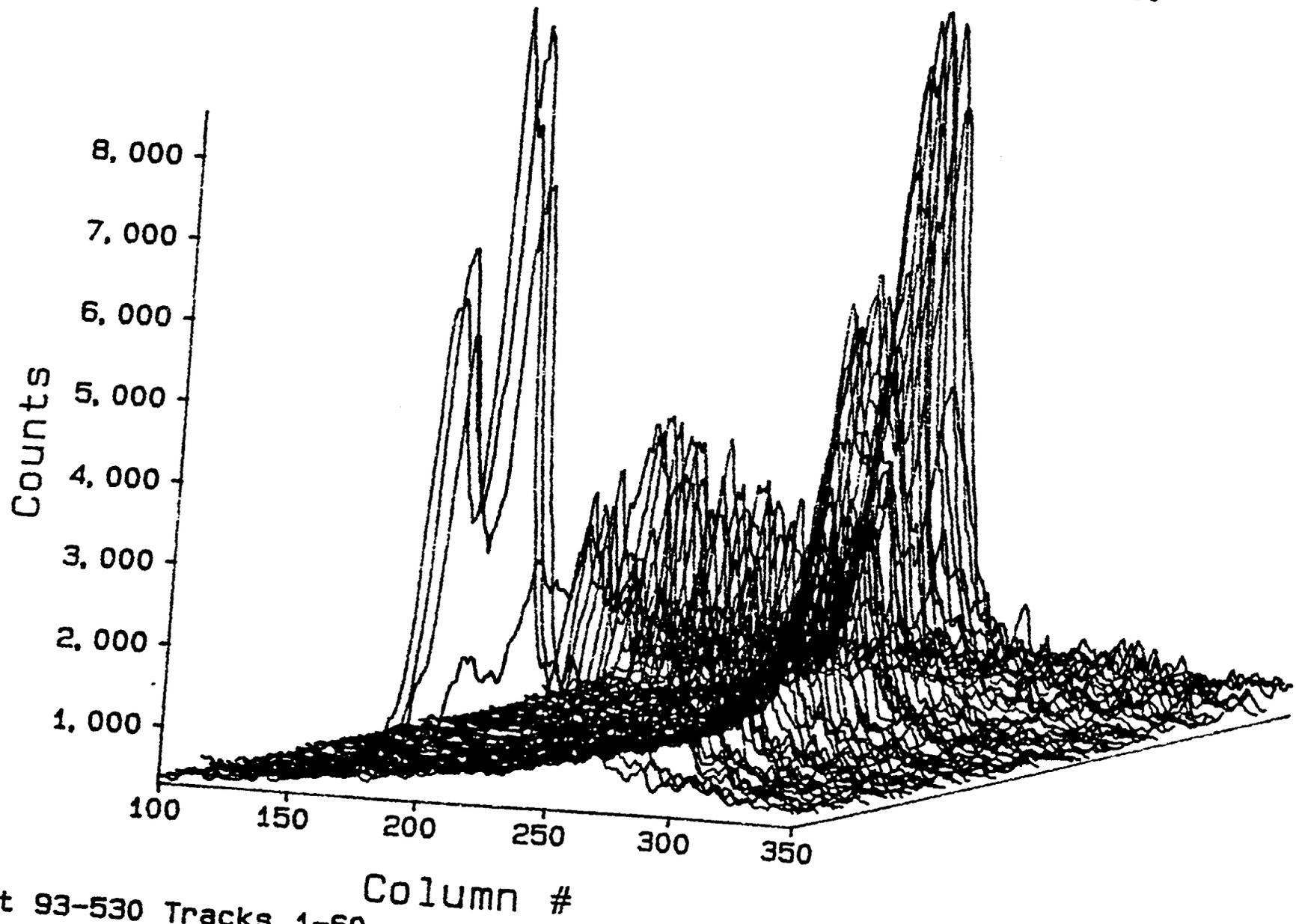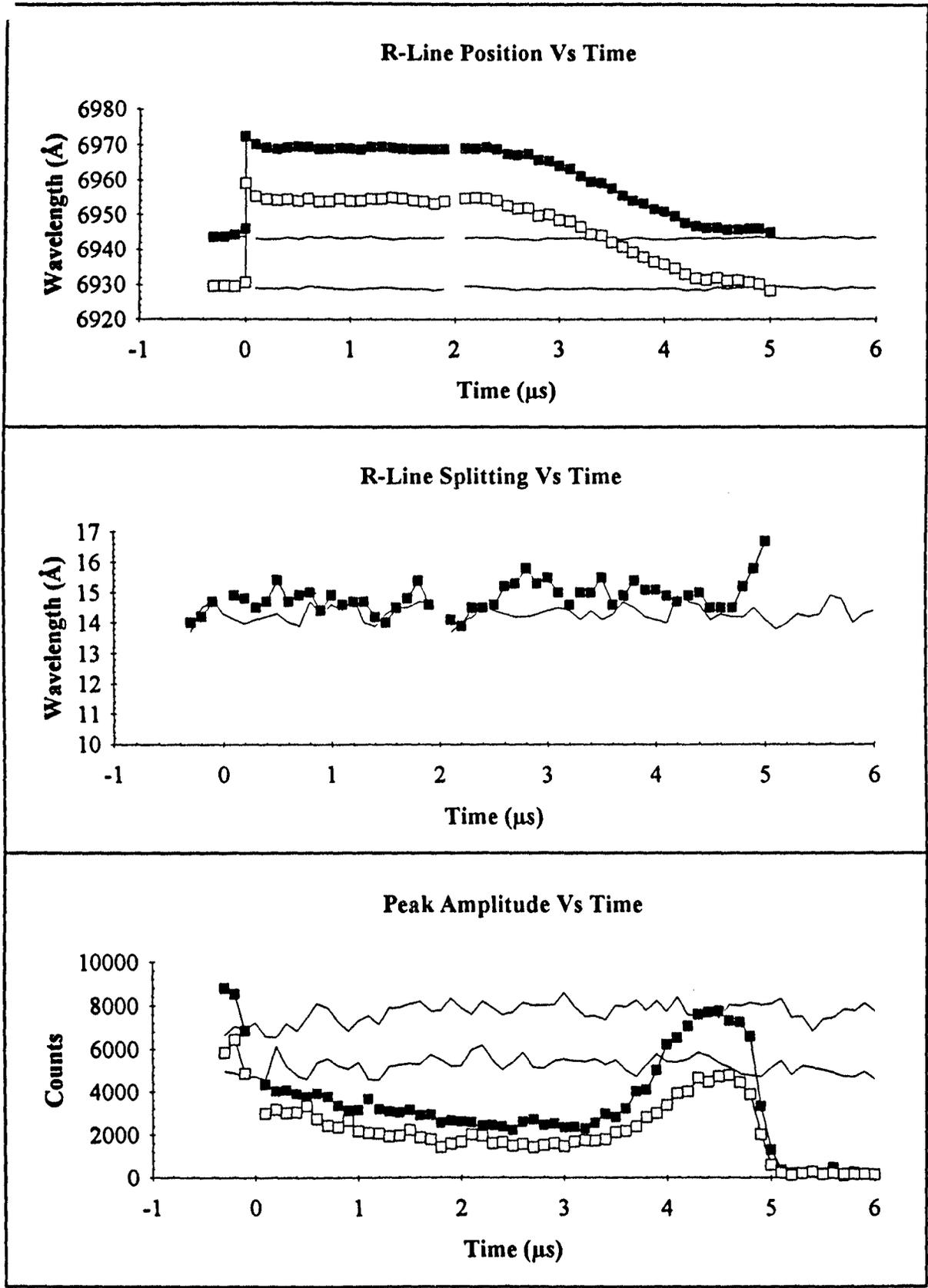
Experimental Configuration for the Ruby Chip Sensor
Shot No. 93-530

Comments:
- $P = 69.3$ kbar
- Ruby was chipped twice in one surface (see shot request form)
- Buffer plate polished
- Recording time = 6 μs

Cu
Flyer

50.8 mm

Measured
Impact Velocity
0.628 km/s

6.35 mm

AL
Target

38.1 mm

Optical Fiber

air, fused silica, 500 μm

A -cut Ruby chip
250 μm thick
0.500 mm
diameter

AL buffer
1.47 mm

19.1 mm

Epoxy Mounting

0: SHOT.DAT Mem: 1. Trk: 1. C: 226. X: 226. Magnitude: 9.590

Shot 93-530 Tracks 1-60

R-Line Position Vs Time

R-Line Splitting Vs Time

Peak Amplitude Vs Time

Date: 29 Sept 93

Shot No. 93-536

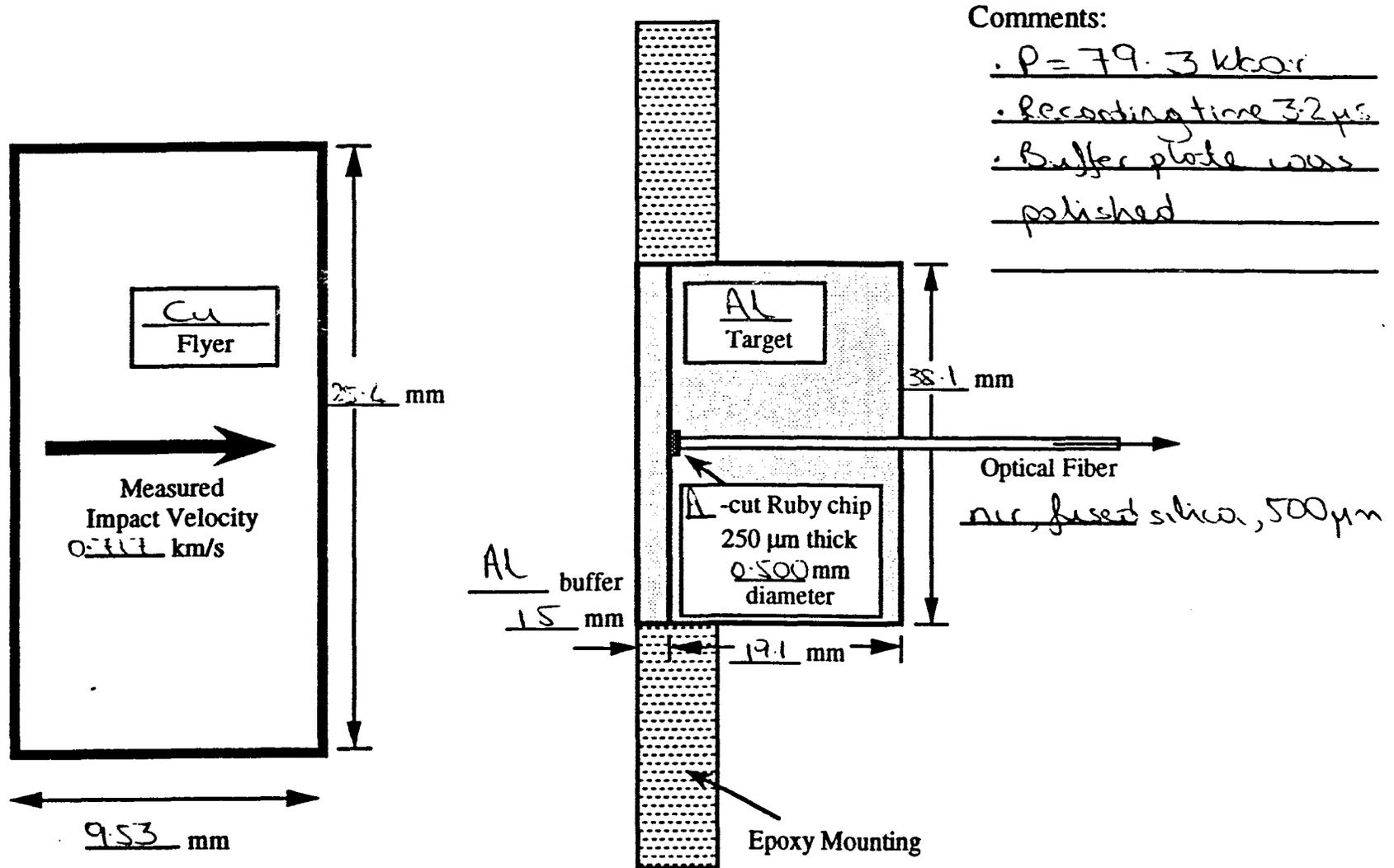## Experimental Configuration and Specifications:

Experimentalist: Dinos Constantinou
Type of Experiment: Uniaxial Strain, Direct Coupling
Stress: 78.6 kbar
R-Line Duration: 3.2 μs
Post Shock Intensity: 31 %
Time/Track: 100 ns
Impact Velocity: 0.717 mm/μs
Ruby Orientation: A-cut
Ruby Dimensions: 0.5 mm diameter x 0.250 mm thick
    method of manufacture: Laser Ablation
Optical Fiber:
    material/diameter: NIR Fused Silica 500 μm diameter
    method of stripping: mechanical
    epoxy used for bond: Norland Optical Adhesive #68
Target Material: Al
Target Dimensions: 38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness: Al / 1.50 mm
    polished (y/n): y
Impactor Material: Cu
Impactor Dimensions: 25.4 mm diameter x 9.53 mm thick
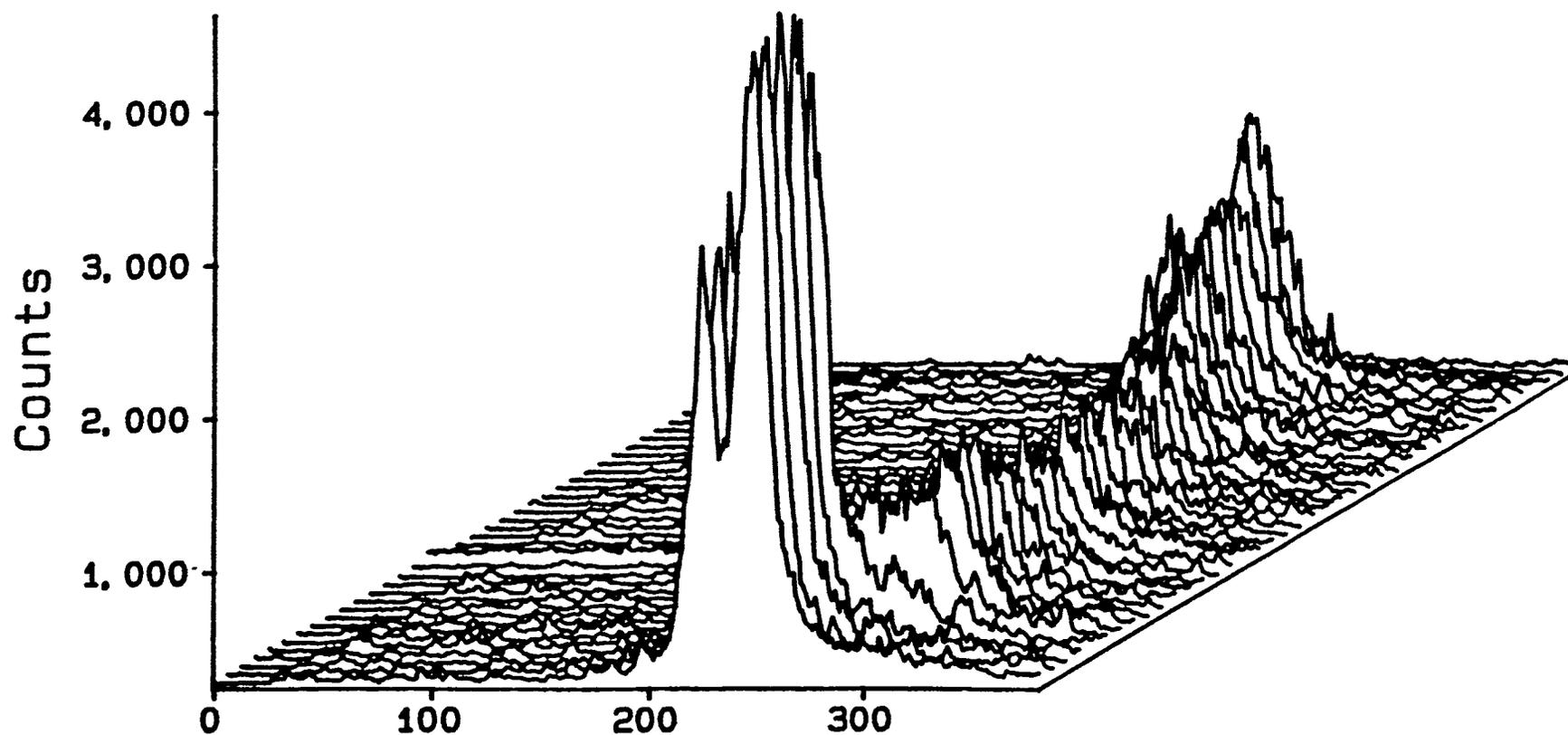
Remarks:

Preparation as in 93-528. This may represent the upper limit in stress up to which
the fused silica fiber could be usefully employed. (see also 93-537)

Date: <u>X   pt 93</u>

Experimental Configuration for the Ruby Chip Sensor
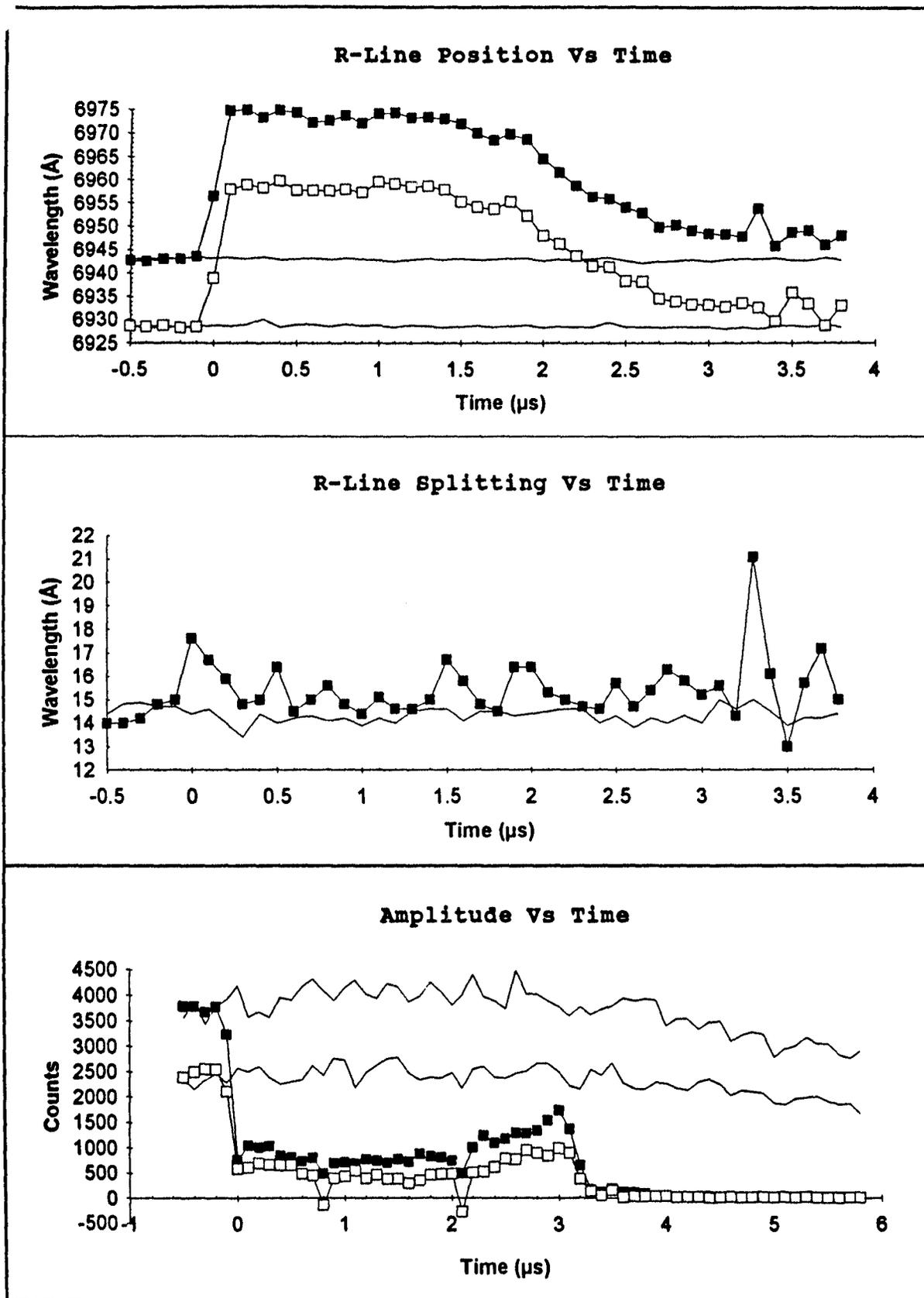# Shot No. <u>93-536</u>

Comments:
- P = 79.3 kbar
- Recording time 3.2 µs
- Buffer plate was polished
_____

Flyer: <u>Cu</u>

<u>25.6</u> mm

Measured
Impact Velocity
0.<u>111</u> km/s

<u>9.53</u> mm

Target: <u>Al</u>

38.1 mm

Optical Fiber

<u>air, fused silica, 500</u> µm

<u>Al</u> -cut Ruby chip
250 µm thick
<u>0.500</u> mm
diameter

<u>Al</u> buffer
<u>15</u> mm

<u>19.1</u> mm

Epoxy Mounting

L Mem: 1, Trk: 2, C: 254, X: 254, Magnitude: 3, 128

29SEPT93 SHOT 93536 TRACKS 1-40

R-Line Position Vs Time

R-Line Splitting Vs Time

Amplitude Vs Time

Date: 4 Oct 93

Shot No. 93-537

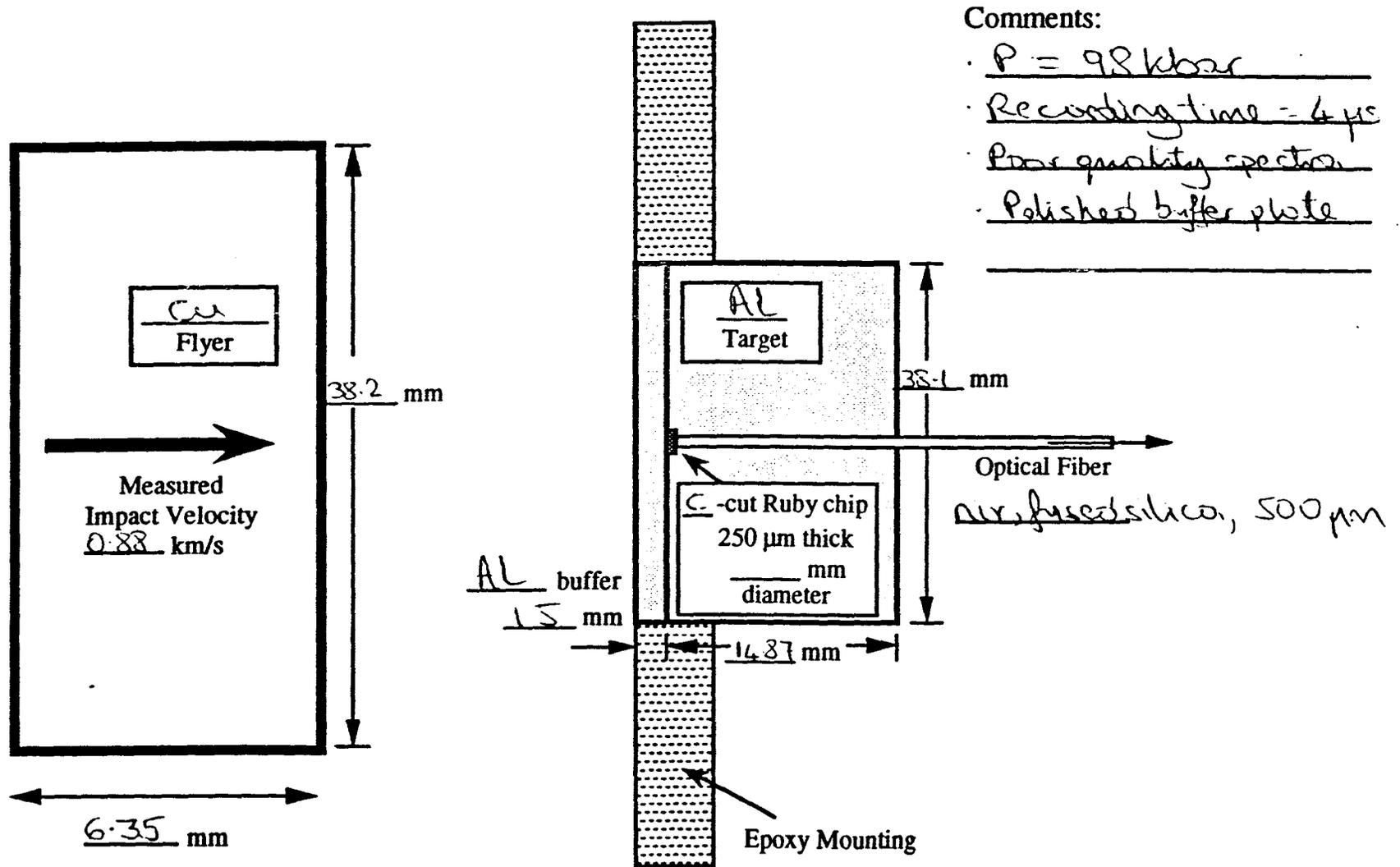## Experimental Configuration and Specifications:

Experimentalist: Dinos Constantinou
Type of Experiment: Uniaxial Strain, Direct Coupling
Stress: 100.2 kbar
R-Line Duration: 4 μs
Post Shock Intensity: 14 %
Time/Track: 100 ns
Impact Velocity: 0.88 mm/μs
Ruby Orientation: C-cut
Ruby Dimensions: 0.5 mm diameter x 0.250 mm thick
   method of manufacture: Laser Ablation
Optical Fiber:
   material/diameter: NIR Fused Silica 500 μm diameter
   method of stripping: mechanical
   epoxy used for bond: Norland Optical Adhesive #68
Target Material: Al
Target Dimensions: 38.1 mm diameter x 14.87 mm thick
Buffer Material/Thickness: Al / 1.5 mm
   polished (y/n): y
Impactor Material: Cu
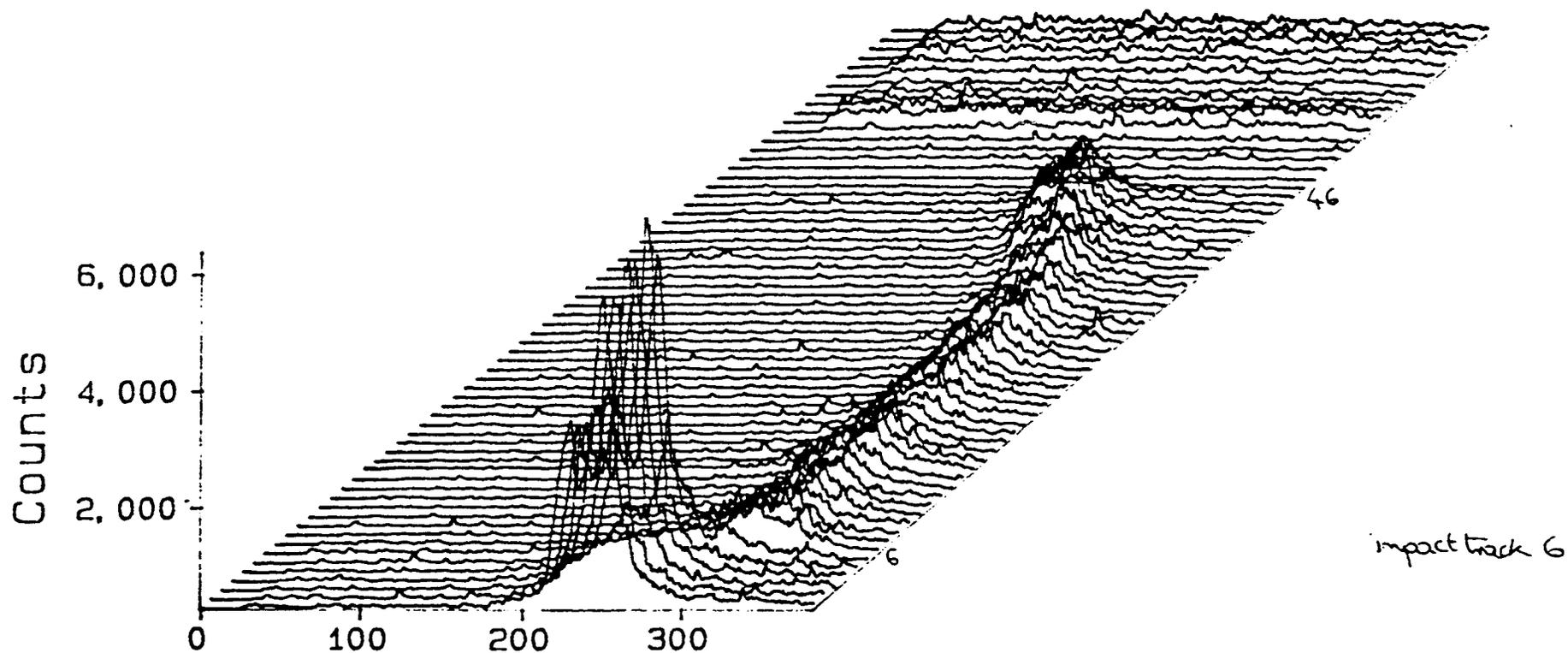Impactor Dimensions: 38.2 mm diameter x 6.35 mm thick

Remarks:

Preparation as in 93-528. The transmitted intensity after the shock arrives at the ruby is unacceptably low. This could conceivably be due to changes in the fused silica fiber taking place at these high stress levels.

Experimental Configuration for the Ruby Chip Sensor
Shot No. 93-537

Comments:
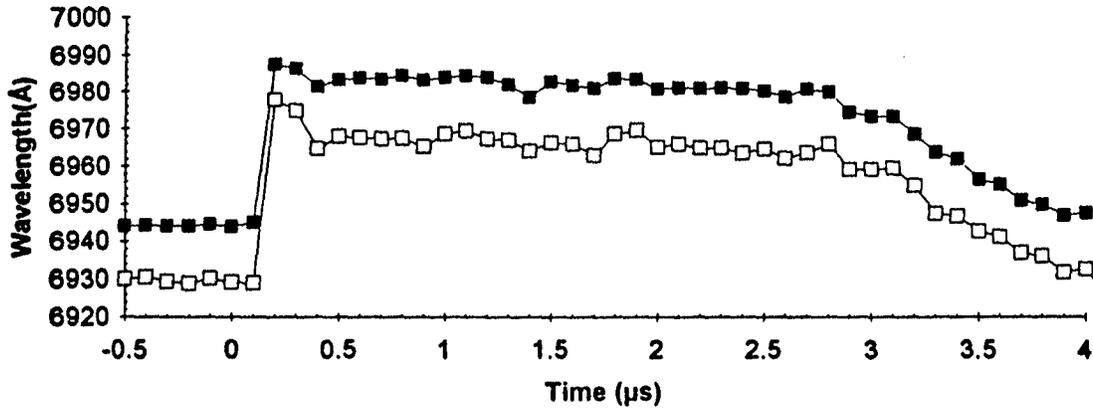
- P = 98 kbar
- Recording time ~ 4 μs
- Poor quality spectra
- Polished buffer plate

___

Cu

Flyer

→

Measured
Impact Velocity
0.88 km/s

38.2 mm

6.35 mm

___

AL

Target

35.1 mm

Optical Fiber

air, fused silica, 500 μm

C -cut Ruby chip
250 μm thick
_____ mm
diameter

AL buffer
15 mm

14.87 mm

Epoxy Mounting

6,000

4,000

Counts

2,000

46

impact track 6

6

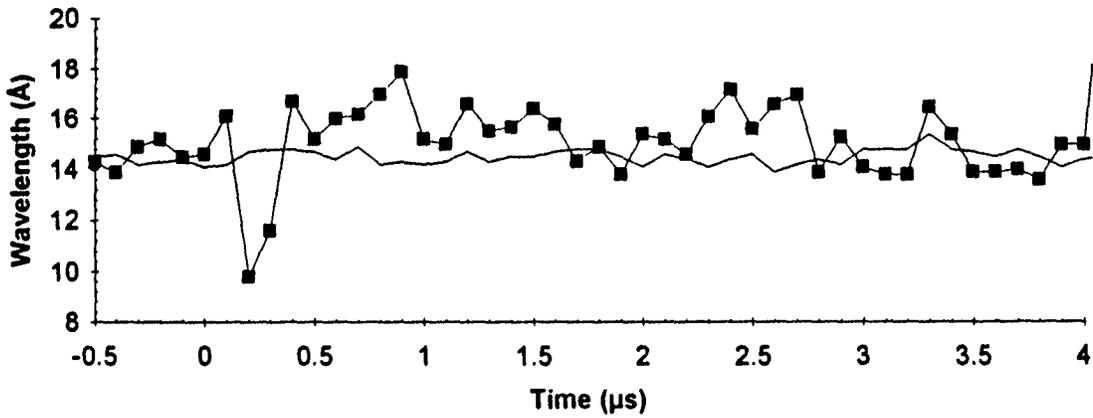0   100   200   300

Column #

4Oct93 Shot 93-537 Tracks 1-64
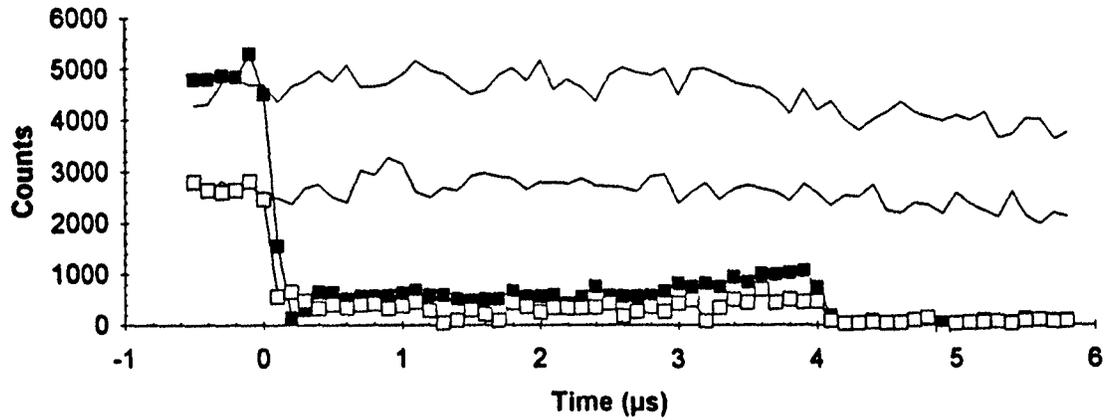
R-Line Peak Position Vs Time

R-Line Splitting Vs Time

Amplitude Vs Time

Date: 23 Aug 93

Shot No.   93-532

Experimental Configuration and Specifications:
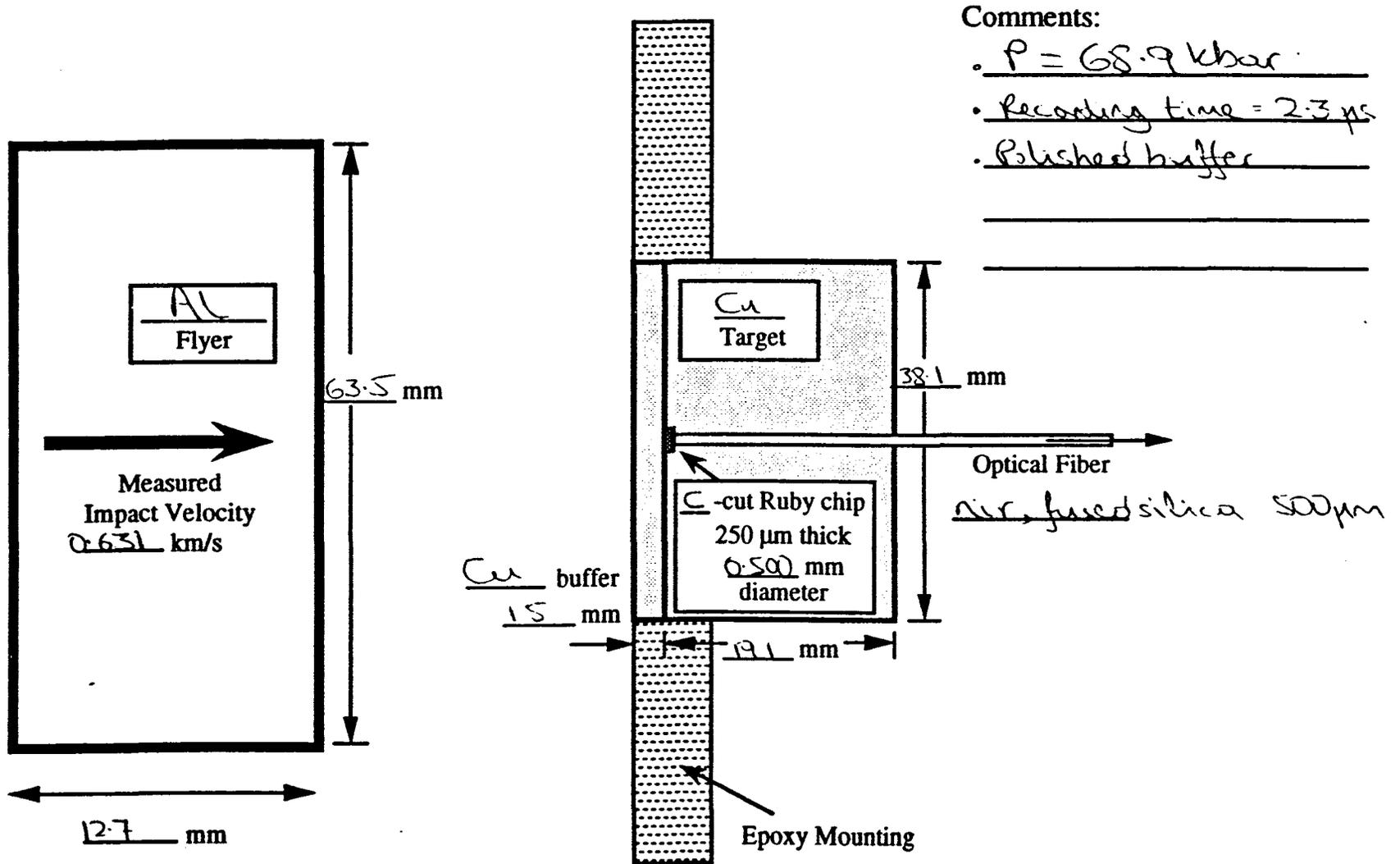
Experimentalist: Dinos Constantinou
Type of Experiment: Uniaxial Strain, Direct Coupling
Stress: 67.5 kbar
R-Line Duration: 2.3 μs
Post Shock Intensity: 50 %
Time/Track: 100 ns
Impact Velocity: 0.631 mm/μs
Ruby Orientation: C-cut
Ruby Dimensions: 0.5 mm diameter x 0.250 mm thick
   method of manufacture: Laser Ablation
Optical Fiber:
   material/diameter: NIR Fused Silica 500 μm diameter
   method of stripping: mechanical
   epoxy used for bond: Norland Optical Adhesive #68
Target Material: Cu
Target Dimensions: 38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness: Cu / 1.50 mm
   polished (y/n):   y
Impactor Material: Al
Impactor Dimensions: 63.5 mm diameter x 12.7 mm thick
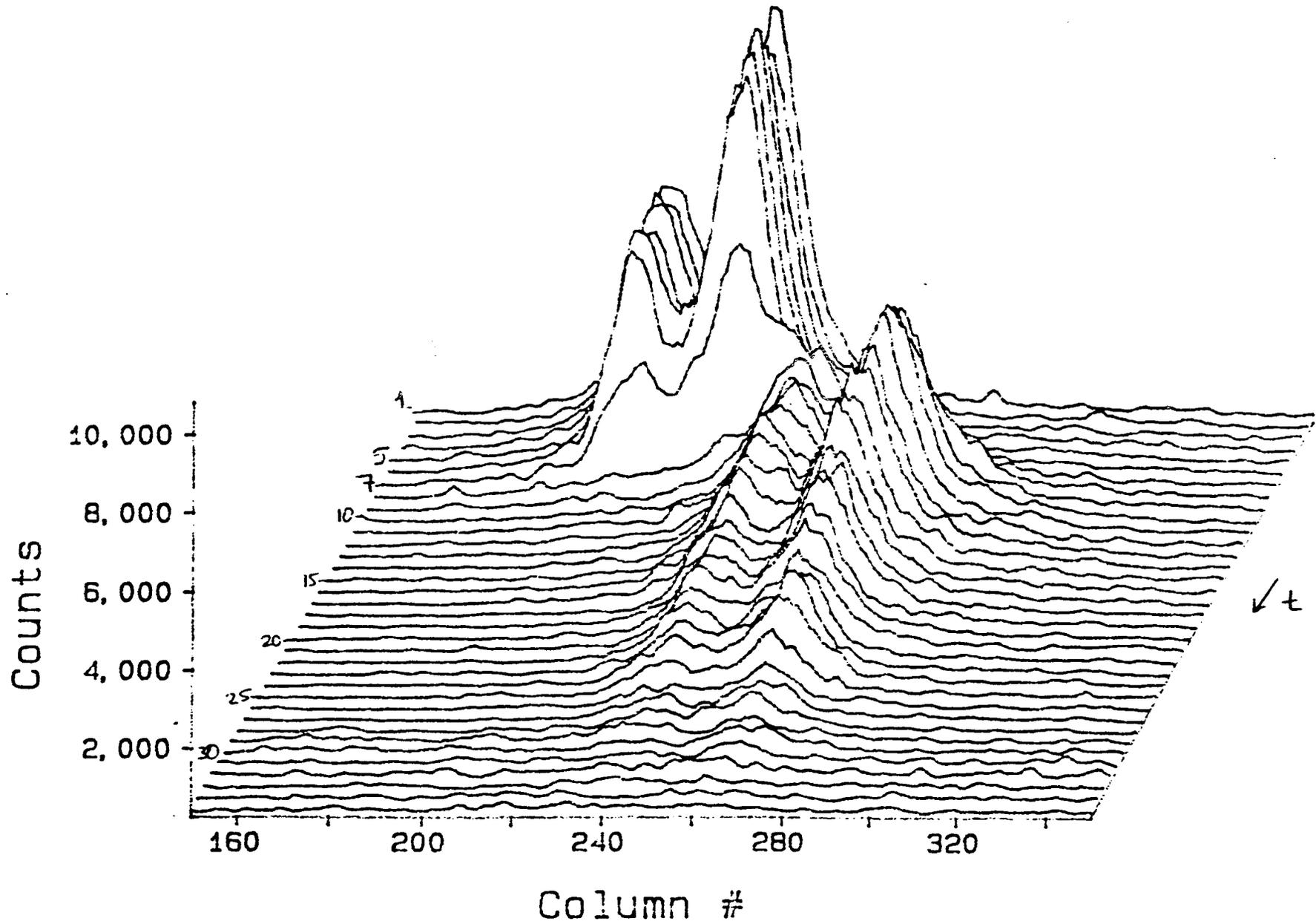
Remarks:

Shot preparation as in 93-528. The signal is lost before any unloading wave comes to the ruby chip. Comparing this experiment with 93-530 (target and impactor materials interchanged) would suggest that the impedance matching between the fiber and the matrix has an important influence on the time duration of transmission of the signal.
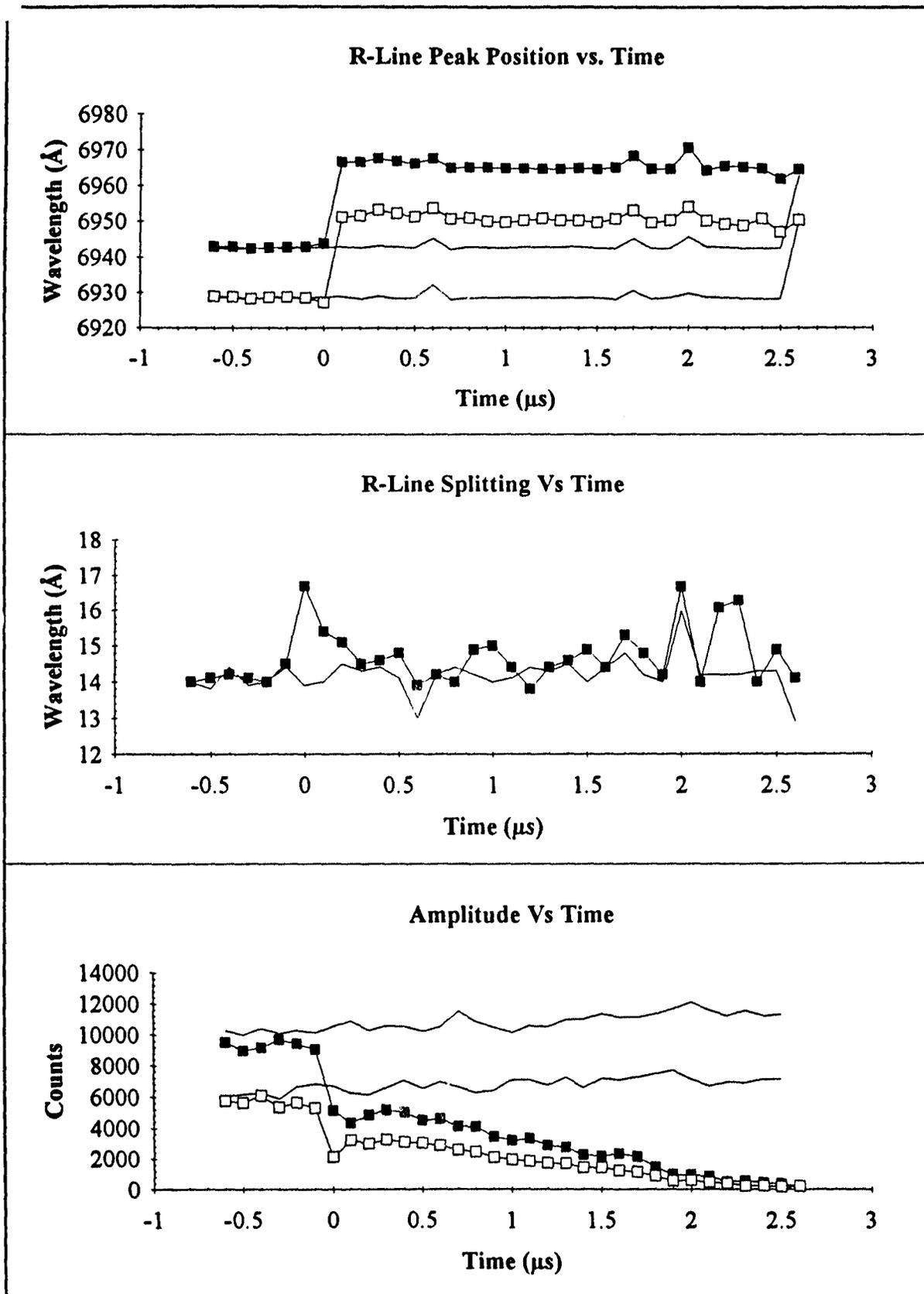
Experimental Configuration for the Ruby Chip Sensor
Shot No. 93-532

Comments:
- $P = 68.9$ kbar
- Recording time = 2.3 µs
- Polished buffer

Al
Flyer

**Measured
Impact Velocity
0.631 km/s**

63.5 mm

12.7 mm

Cu
Target

38.1 mm

Optical Fiber

air fused silica 500µm

C -cut Ruby chip
250 µm thick
0.500 mm
diameter

Cu buffer
15 mm

19.1 mm

Epoxy Mounting

O: SHOT.DAT Mem: 1, Trk: 19, C: 88, X: 88, Magnitude: 324

R-Line Peak Position vs. Time

R-Line Splitting Vs Time

Amplitude Vs Time

Appendix D

Detailed experimental results: Rod Impact Experiments
D1: 93519
D2: 93529
D3: 93531

Date: 6/15/93

Shot No.   93-519
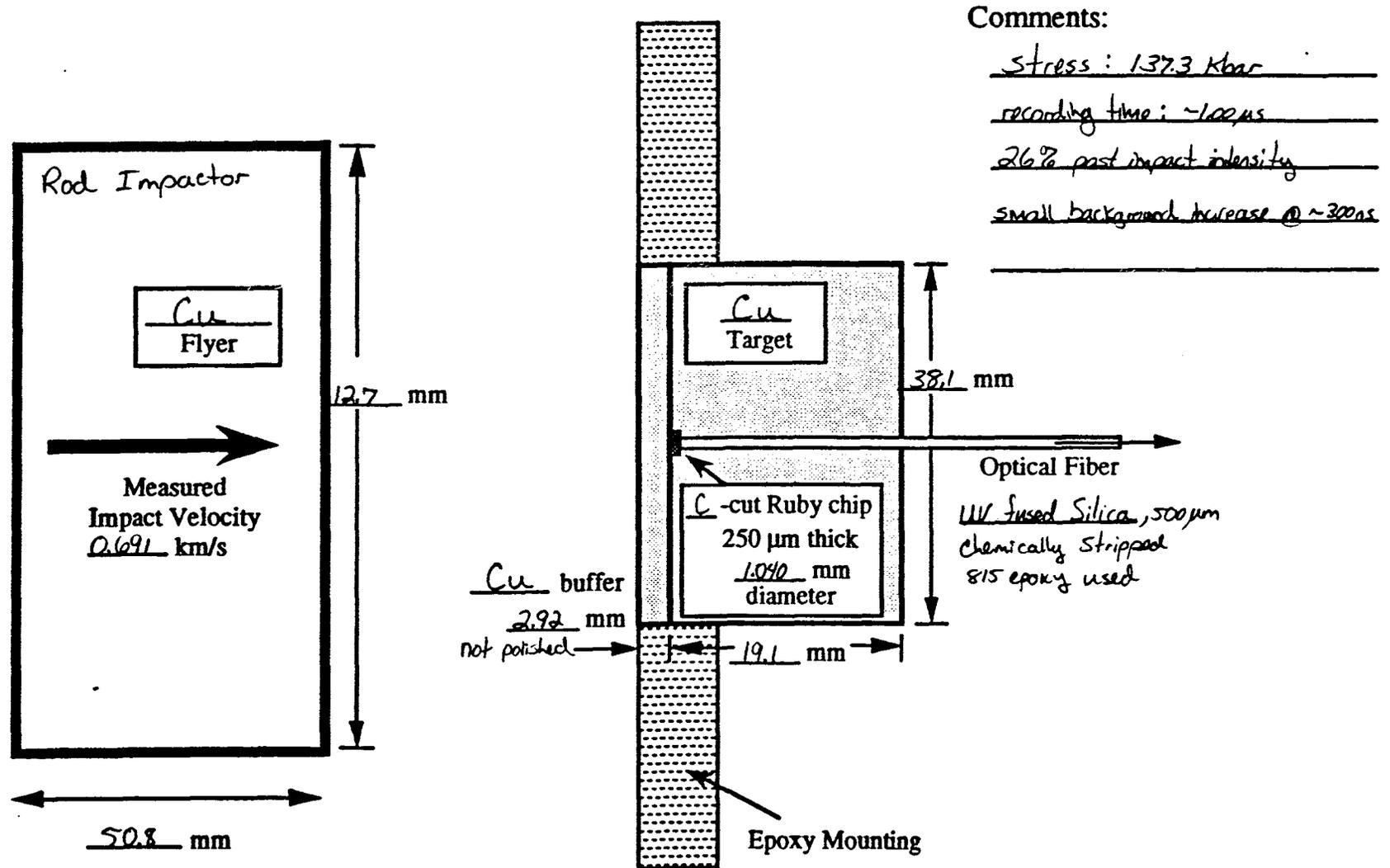
Experimental Configuration and Specifications:

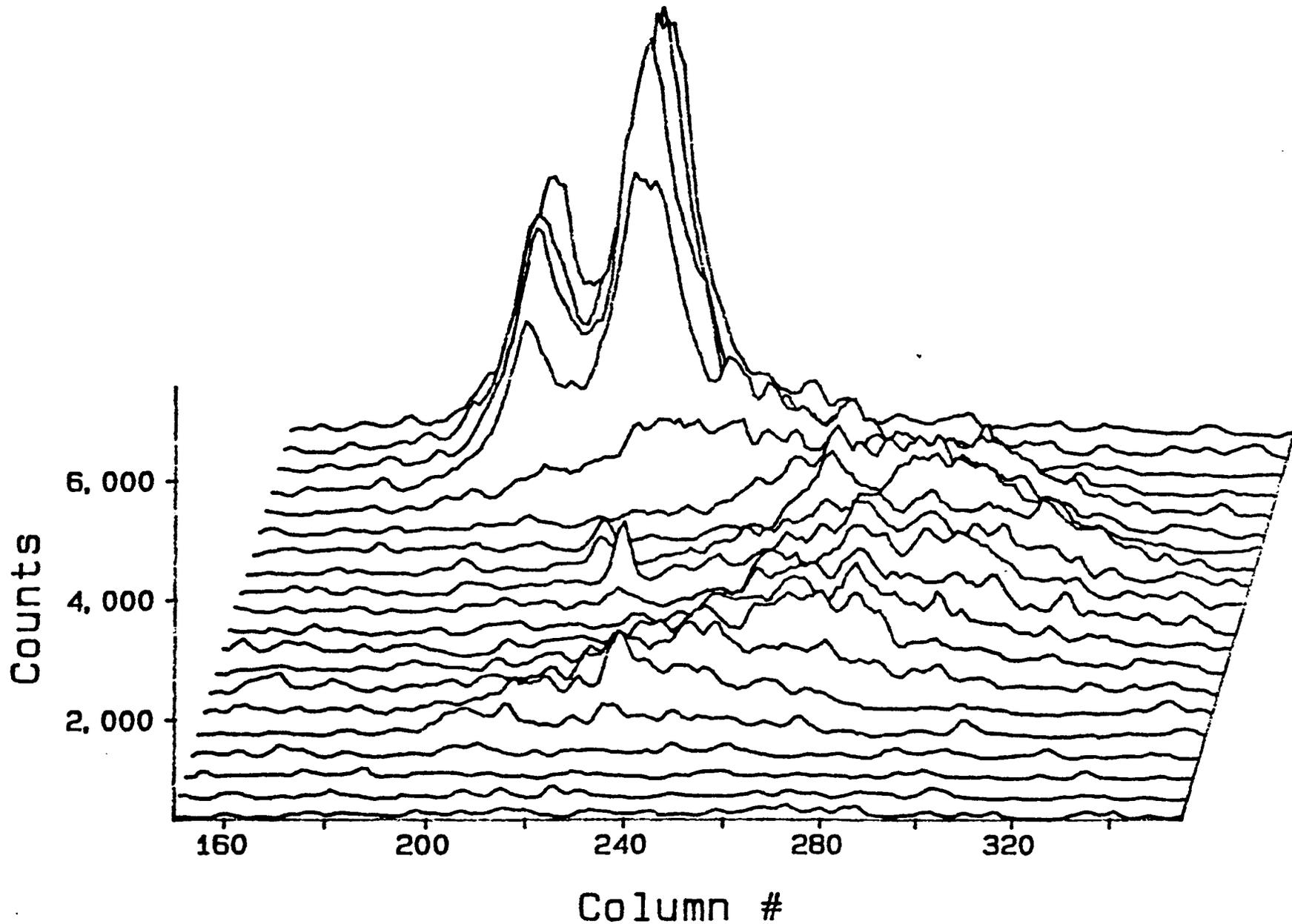|	
Experimentalist:	Kurt Zimmerman
Type of Experiment:	Rod Impact, Direct Coupling
Stress:	131.3 kbar
R-Line Duration:	~1.0 μs
Post Shock Intensity:	26% steady decrease
Time/Track:	100 ns
Impact Velocity:	0.691 mm/μs
Ruby Orientation:	C-cut
Ruby Dimensions:	1.08 mm diameter x 0.250 mm thick
method of manufacture:	Impact Grinder
Optical Fiber:	
material/diameter:	UV Fused Silica / 500 μm
method of stripping:	chemical
epoxy used for bond:	815 Epoxy
Target Material:	Cu
Target Dimensions:	38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness:	Cu / 2.92 mm
polished (y/n):	n
Impactor Material:	Cu
Impactor Dimensions:	12.7 mm diameter x 50.8 mm long

Remarks:

The two peaks are never clearly discernible. There is a slight background increase after 300 ns and a substantial background increase after 3.1 μs. The signal begins to shift back toward ambient after 800 ns. The ruby chip was cleaned in potassium hydroxide then rubbed clean. The tip of the fiber looked good and clean. I glued the ruby chip on by hand without a jig; the amount of epoxy may have been excessive but I was able to rub the ruby down somewhat. No pressure was applied to the chip and fiber during curing. The buffer plate and the fiber with attached ruby chip were glued together all at once. The buffer was rubbed down and clamped in place with 4 C-clamps. (It is possible that the ruby chip came loose from the fiber at this point since the data looks bad.) The ruby chip was <10 μm above the surface of the target.
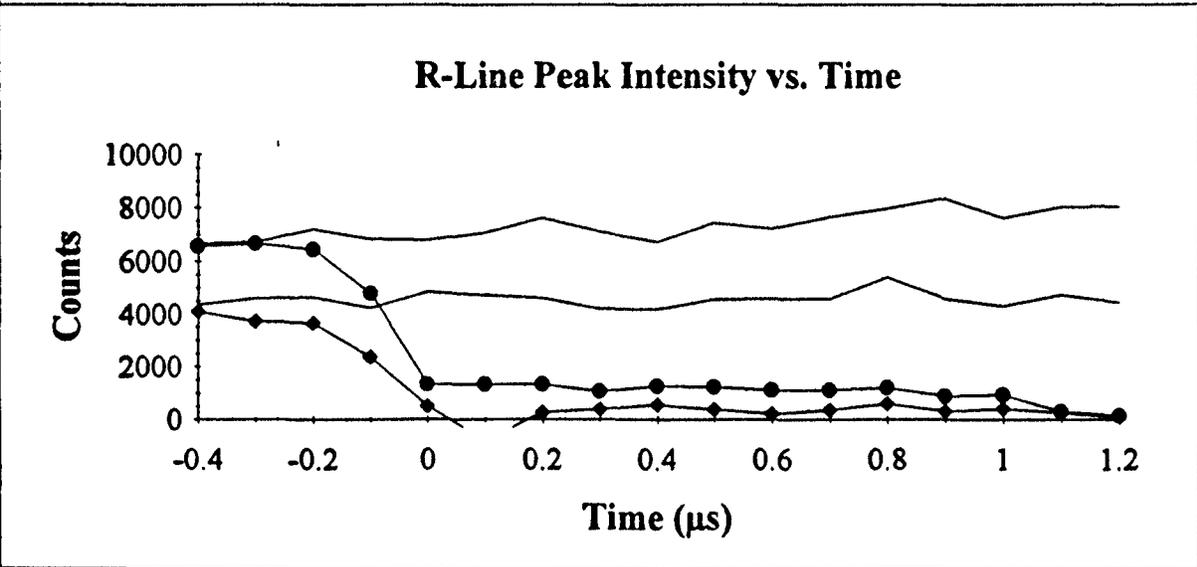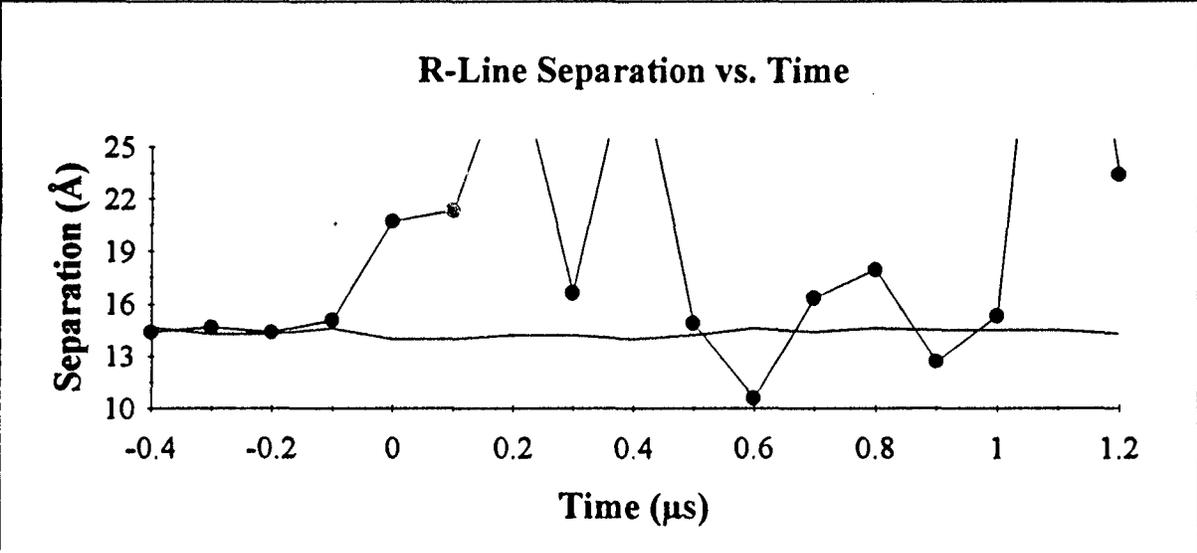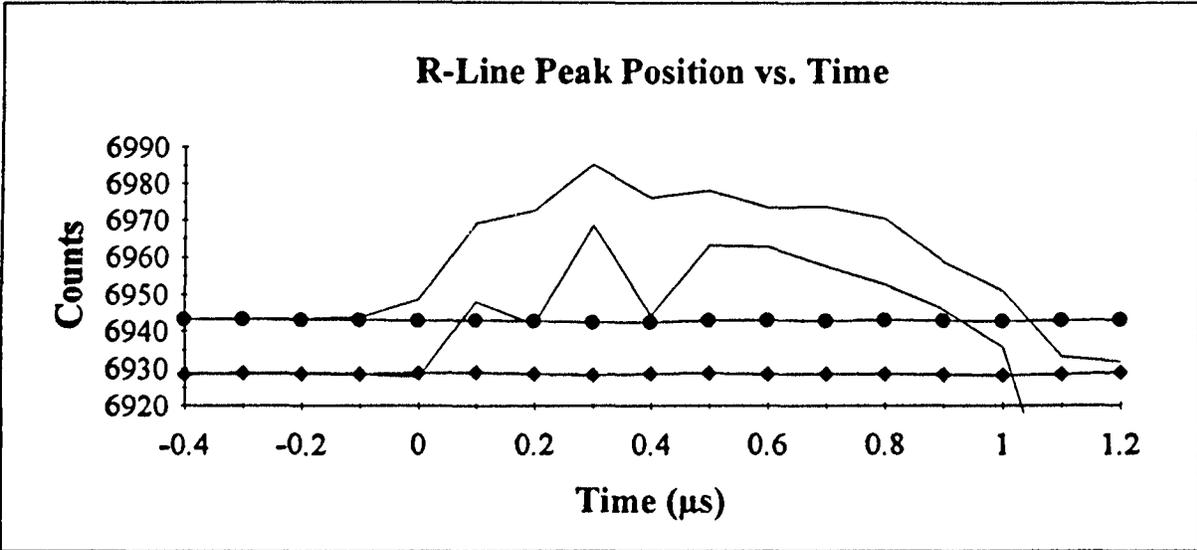
Date: 6/15/93

Experimental Configuration for the Ruby Chip Sensor
Shot No. 93-519

Rod Impactor

Cu
Flyer

12.7 mm

Measured
Impact Velocity
0.691 km/s

50.8 mm

Cu
Target

38.1 mm

Optical Fiber

C -cut Ruby chip
250 μm thick
1.040 mm
diameter

UV fused Silica, 500 μm
Chemically Stripped
815 epoxy used

Cu buffer
2.92 mm
not polished

19.1 mm

Epoxy Mounting

Comments:

Stress : 137.3 Kbar

recording time : ~100 μs

26% past impact intensity

small background increase @ ~300 ns

O: SHOT.DAT Mem: 1, Trk: 1, C: 15, X: 15, Magnitude: 347

SHOT #93-519 1mm RUBY IN Cu MATRIX

R-Line Peak Position vs. Time

R-Line Separation vs. Time

R-Line Peak Intensity vs. Time

Date: 8/17/93

Shot No. 93-529

Experimental Configuration and Specifications:

Experimentalist: Kurt Zimmerman
Type of Experiment: Rod Impactor, Direct Coupling
Stress: 67.3 kbar
R-Line Duration: 6.0+ µs
Post Shock Intensity: 50% during compression, 0% upon release
Time/Track: 100 ns
Impact Velocity: 0.629 mm/µs
Ruby Orientation: C-cut
Ruby Dimensions: 0.50 mm diameter x 0.250 mm thick
    method of manufacture: Laser Ablation
Optical Fiber:
    material/diameter: NIR Fused Silica / 500 µm
    method of stripping: chemical
    epoxy used for bond: Norland Optical Adhesive #68
Target Material: Al
Target Dimensions: 38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness: Al / 1.50 mm
    polished (y/n): y
Impactor Material: Cu
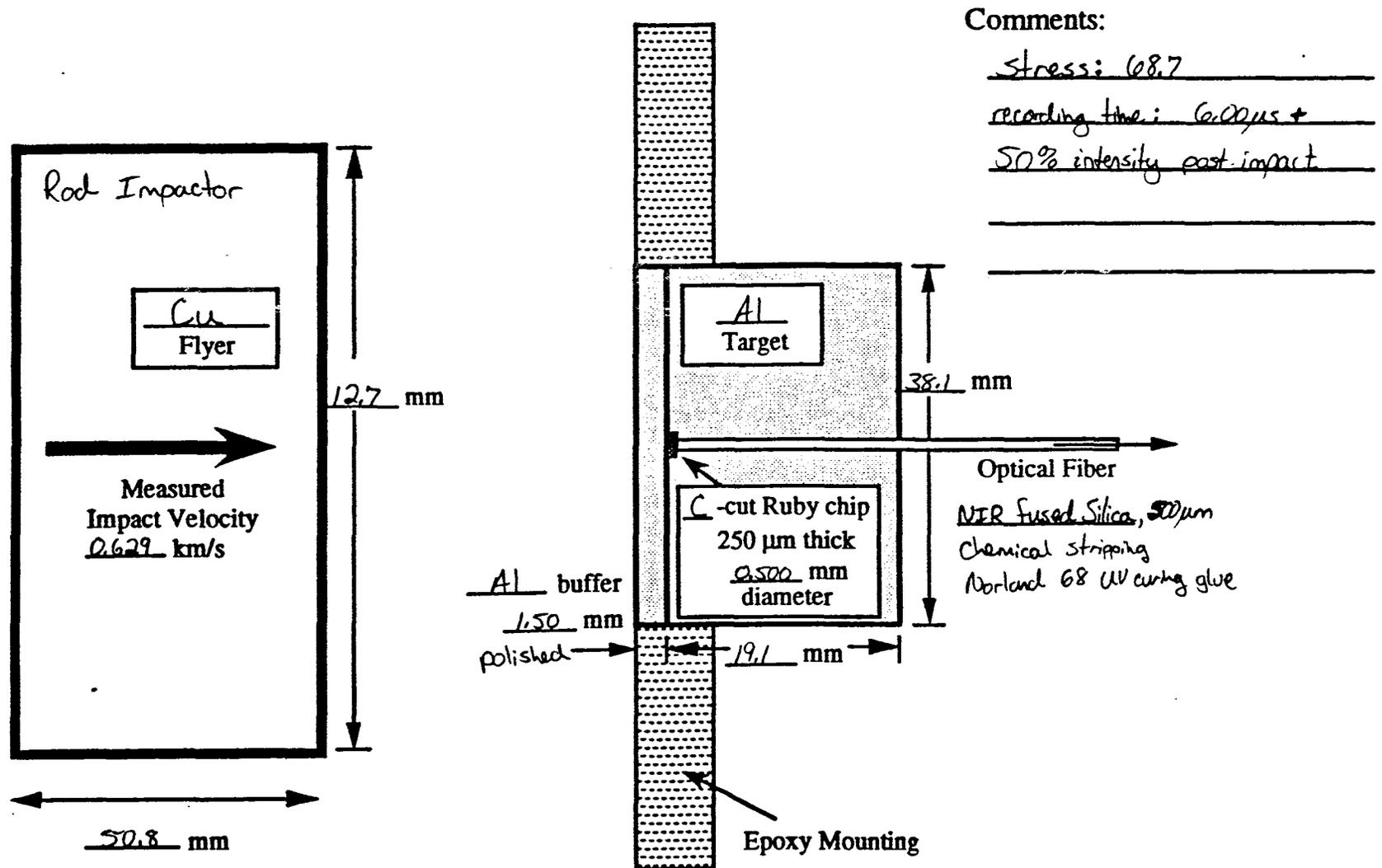Impactor Dimensions: 12.7 mm diameter x 50.8 mm thick

Remarks:

The signal was clear with the two peaks discernible throughout the 6.0 µs data acquisition time. As the R-lines shift back toward ambient after ~700 ns, the signal intensity begins to rise, and in fact is about 1000 counts above ambient for about 500 ns. There is a gradual shift of the R-line peak position between 2.8 µs and 4.1 µs, during which time the intensity drops to a value near ambient. After 4.1 µs the R-line position looks to be roughly constant. By integrating the counts across the observed spectrum it is observed that the total number of counts does in fact change from track to track. The fiber had three small chips on the outer edge. The bond between the fiber and ruby looked clean and uniform with only one small particle observable toward the outside of the core region. The angle of the walls in the target was measured to be ~0.7 mrad. This seems to be consistent for several targets.
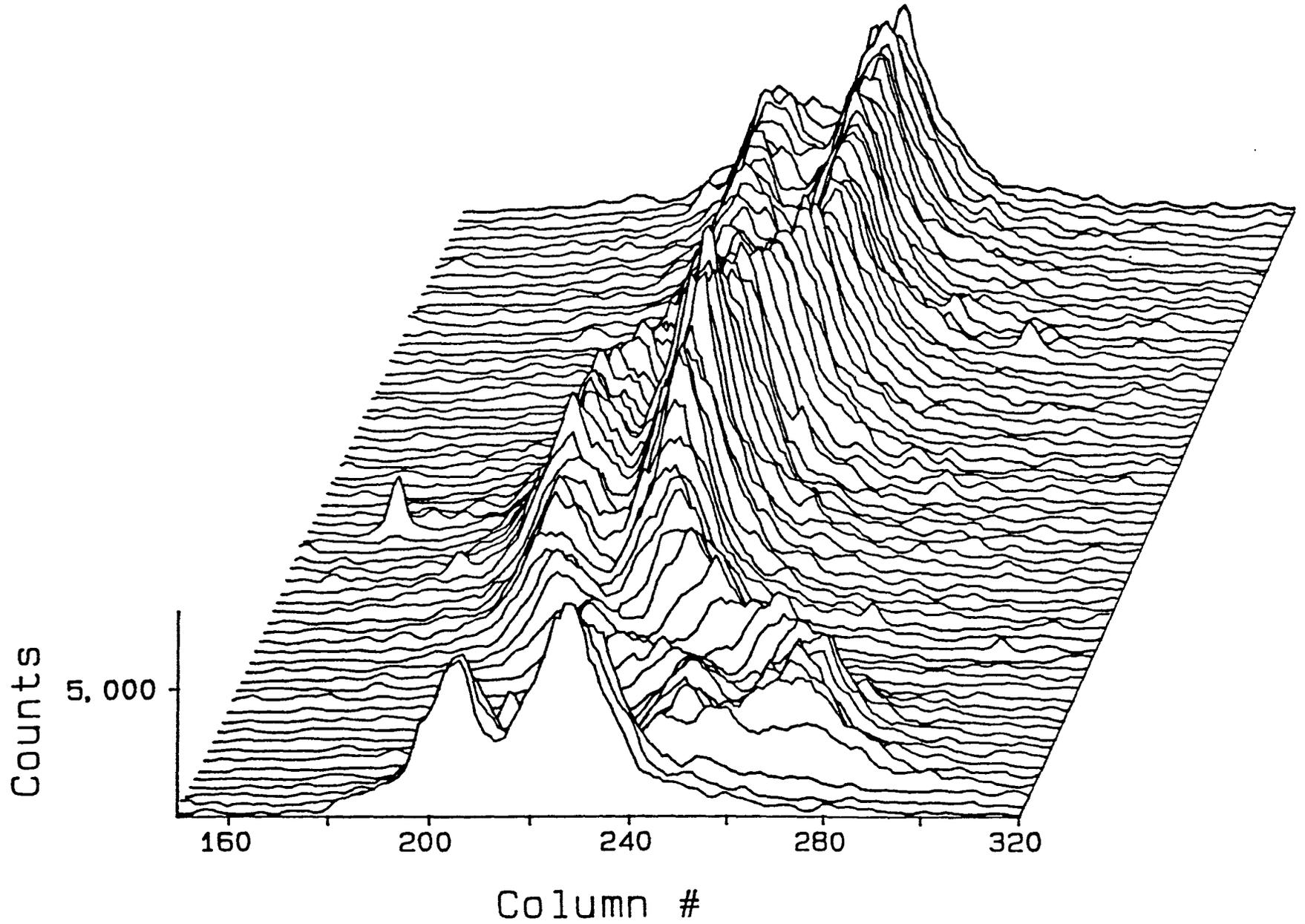
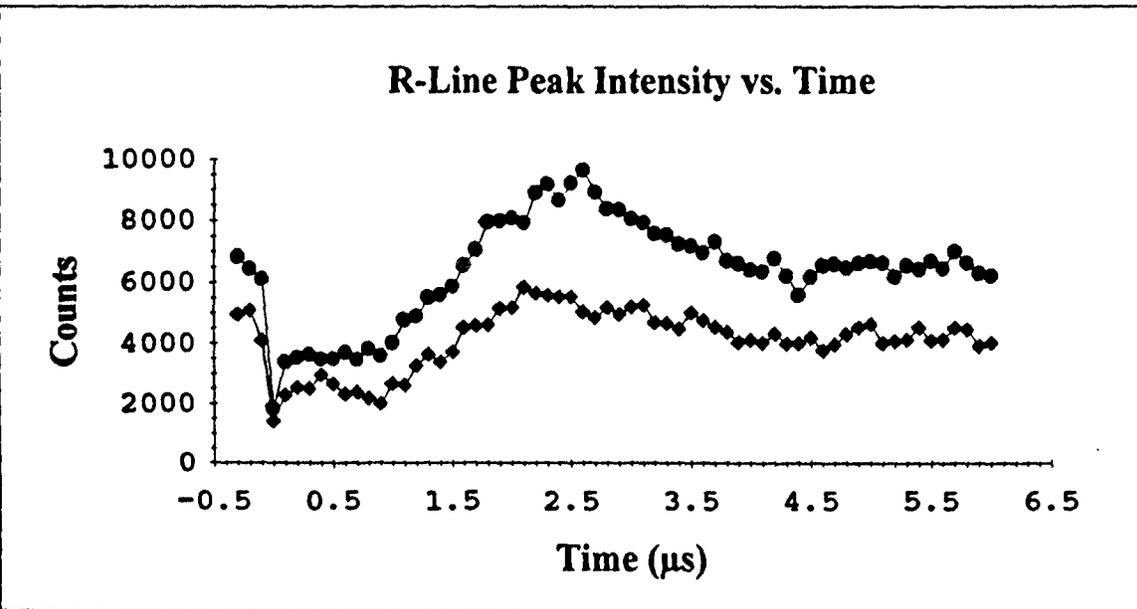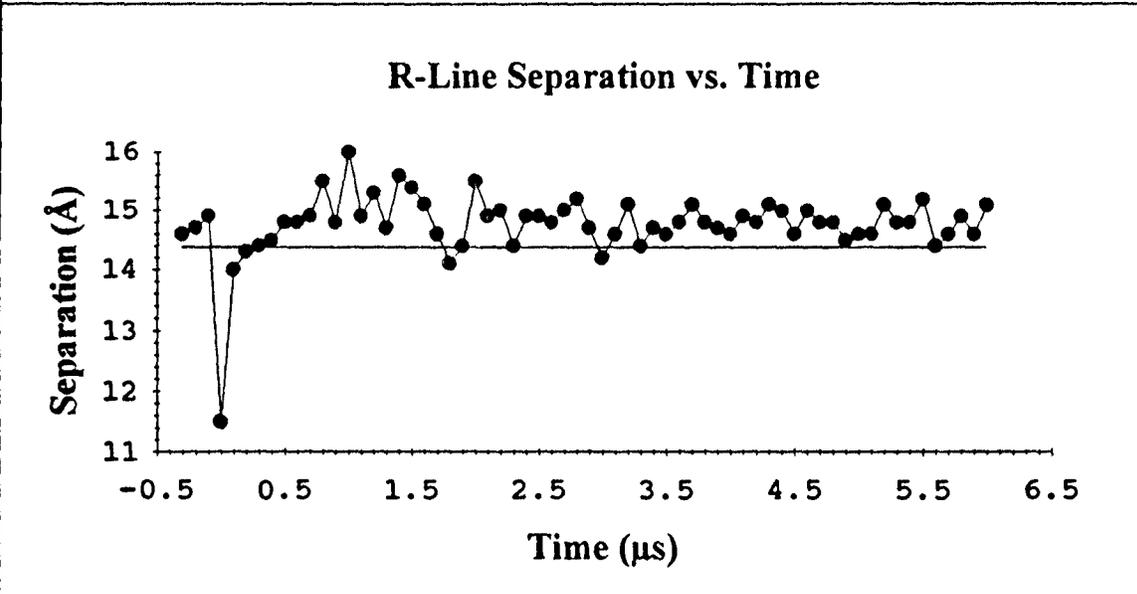# Experimental Configuration for the Ruby Chip Sensor
Shot No. 93-529

Comments:

Stress: 68.7

recording time: 6.00µs +

50% intensity post-impact

Rod Impactor

| Cu |
| Flyer |

12.7 mm

Measured
Impact Velocity
0.629 km/s

50.8 mm

| Al |
| Target |

38.1 mm

Optical Fiber

C -cut Ruby chip
250 µm thick
0.500 mm
diameter

NIR fused Silica, 500µm
Chemical stripping
Norland 68 UV curing glue

Al buffer
1.50 mm
polished

19.1 mm

Epoxy Mounting

O: SHOT.DAT Mem: 1, Trk: 1, C: 0, X: 0, Magnitude: 322
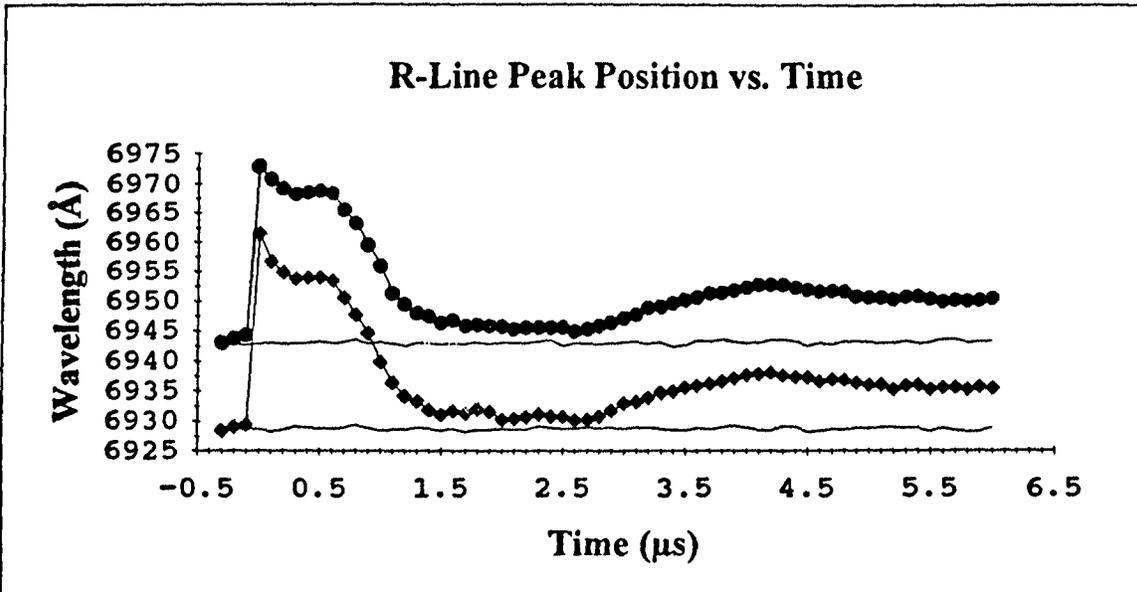
Date: 8/20/93

Shot No.   93-531

Experimental Configuration and Specifications:
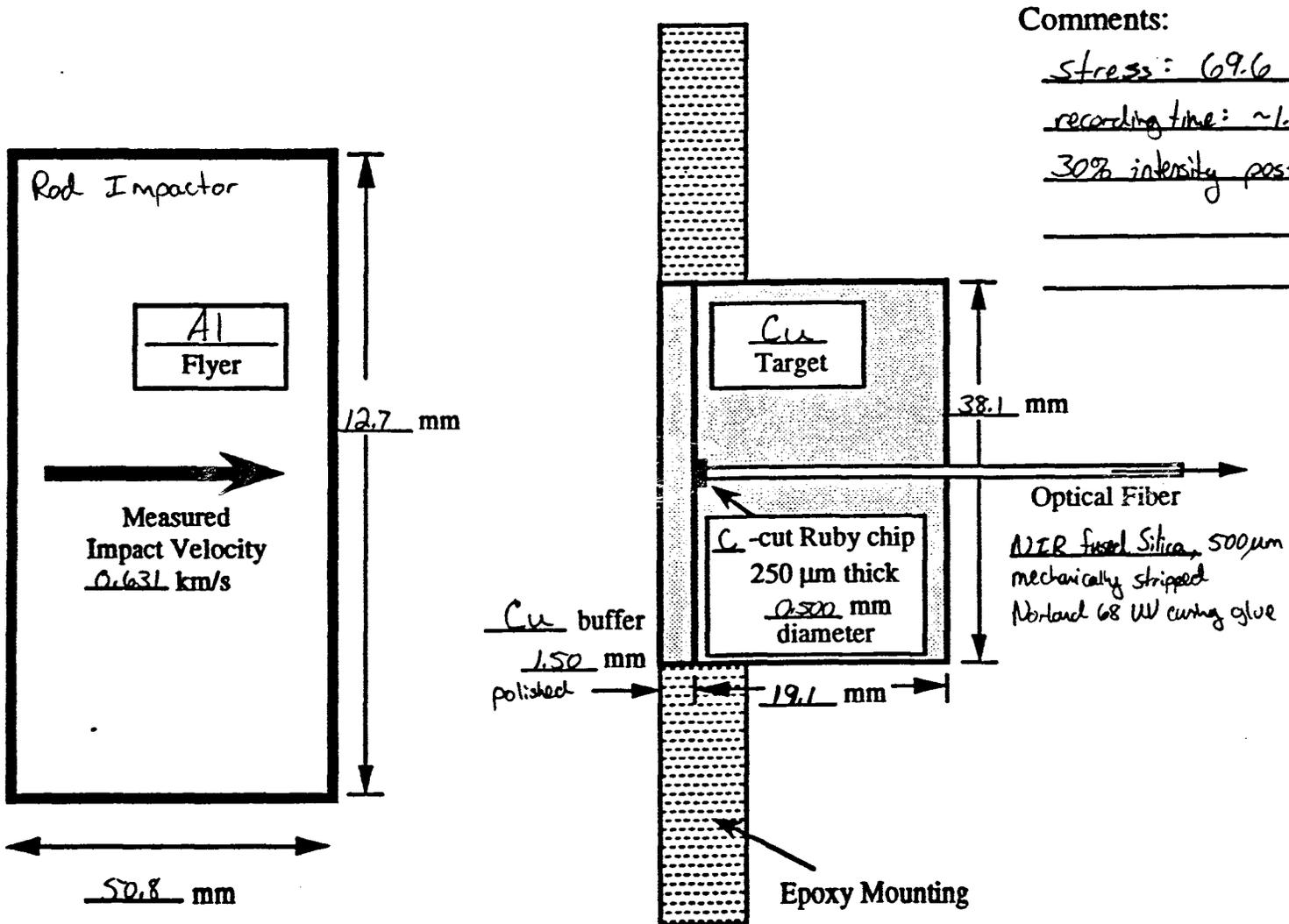
Experimentalist: Kurt Zimmerman
Type of Experiment: Rod Impactor, Direct Coupling
Stress: 67.5 kbar
R-Line Duration: ~1.5 µs
Post Shock Intensity: 30% steady decrease
Time/Track: 150 ns
Impact Velocity: 0.631 mm/µs
Ruby Orientation: C-cut
Ruby Dimensions: 0.49 mm diameter x 0.250 mm thick
     method of manufacture: Laser Ablation
Optical Fiber:
     material/diameter: NIR Fused Silica / 500 µm
     method of stripping: mechanical
     epoxy used for bond: Norland Optical Adhesive #68
Target Material: Cu
Target Dimensions: 38.1 mm diameter x 19.1 mm thick
Buffer Material/Thickness: Cu / 1.50 mm
     polished (y/n):   y
Impactor Material: Al
Impactor Dimensions: 12.7 mm diameter x 50.8 mm thick

Remarks:

The intensity of the peaks dropped significantly under compression but the R-line peaks are discernible throughout most of the experiment. There was no background increase observed over the duration of the experiment. The shot was prepared identically to #93-529 but the target and rod impactor materials are interchanged. It appears that the mismatch in shock impedance between the copper and the fused silica is enough to inhibit the survival of the fiber.

Date: _8/20/93_

Experimental Configuration for the Ruby Chip Sensor
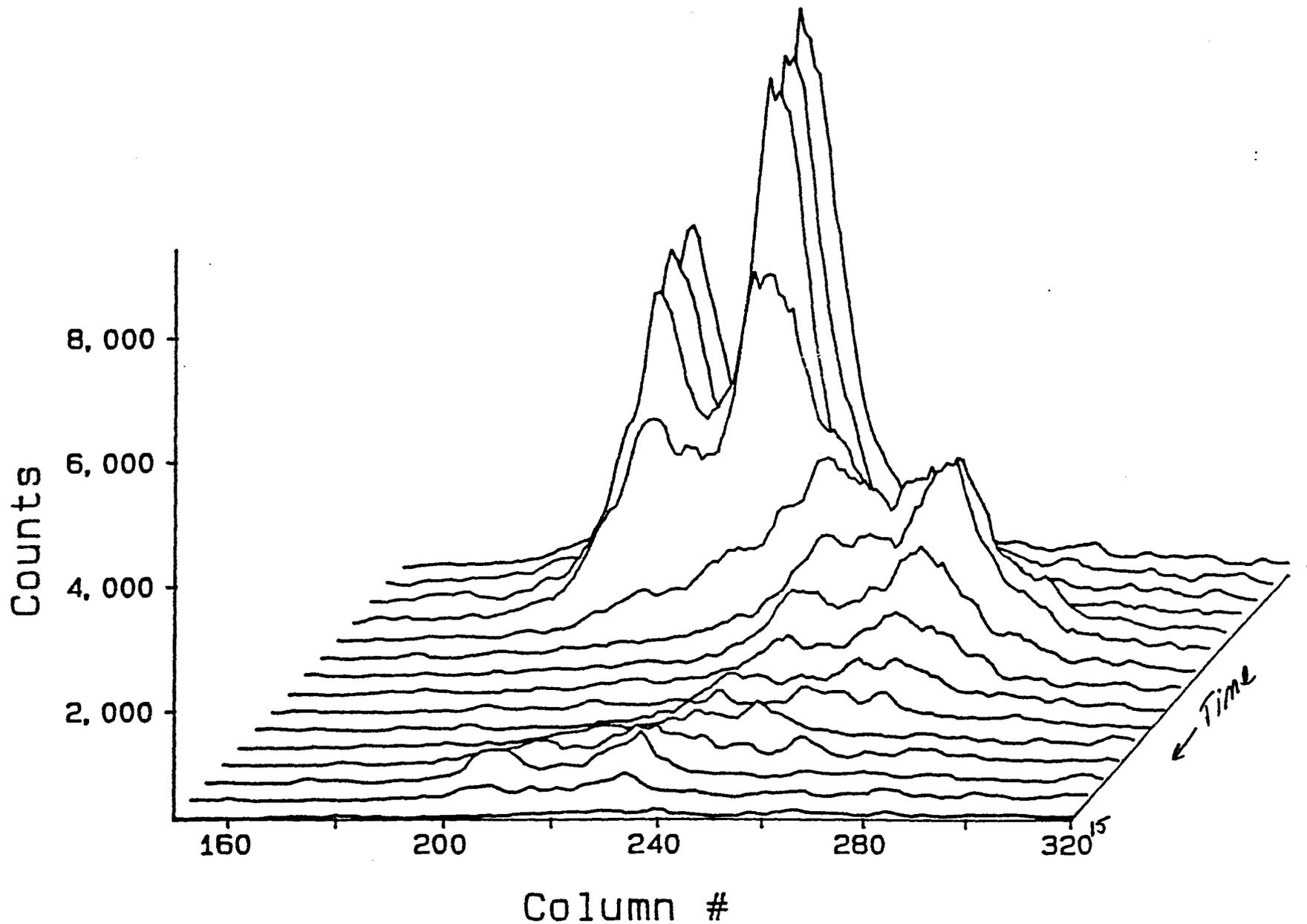## Shot No. _93-531_

Comments:

Stress: 69.6

recording time: ~1.50 µs

30% intensity post-impact

Rod Impactor

A1
Flyer

_12.7_ mm

**Measured
Impact Velocity
_0.631_ km/s**

_50.8_ mm

Cu
Target

_38.1_ mm

Optical Fiber

NIR fused Silica, 500µm
mechanically stripped
Norland 68 UV curing glue

_C_ -cut Ruby chip
250 µm thick
_0.500_ mm
diameter

_Cu_ buffer
_1.50_ mm
polished

_19.1_ mm

Epoxy Mounting

O: SHOT.DAT Mem: 1, Trk: 14, C: 150, X: 150, Magnitude: 324

SHOT #93-531 Al ON Cu, 70 kbar

R-Line Peak Position vs. Time

R-Line Separation vs. Time

R-Line Peak Intensity vs. Time