INTERNAL REPORT SDL-85-04

MEASUREMENT OF THE PRESSURE-TIME PROFILE OF A MULTIPLY SHOCKED FLUID USING AN ELECTROMAGNETIC PARTICLE VELOCITY GAUGE

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Introduction

The original goal of this work was to measure the shear response of fused silica. One pure compression experiment (S85-523) was done before the project took on a new direction. The new objective was to try to measure the pressure-time profile of a thin multiply-shocked liquid layer.

Approach

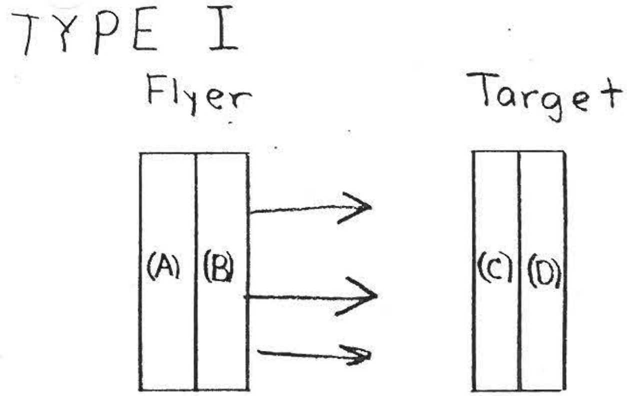
A schematic of the experimental approach is illustrated by configuration III of Fig. 1.1. A flyer impacts a target in which a thin layer of CS_2 is trapped between two materials of higher shock impedance. A shock will propagate into materials A and B. The shock in B will travel into material C layer and reverberate between the cell walls. A electromagnetic particle velocity gauge located at the material C-material D boundary will measure the particle velocity history of this boundary. The theory and approach of these experiments are very similar to experiments described in Refs. 1 and 2.

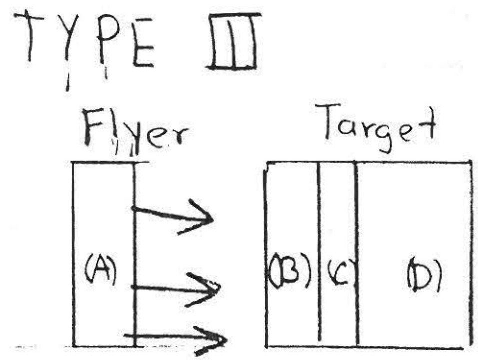
Cell body, shim and gauge design

Cell design

The cell designs used are illustrated by Figs. 1.2 and 1.3. The cell bodys were constructed of type II PMMA

DATE	SYM	REVISION RECORD	AUTH.	DR.	CK.





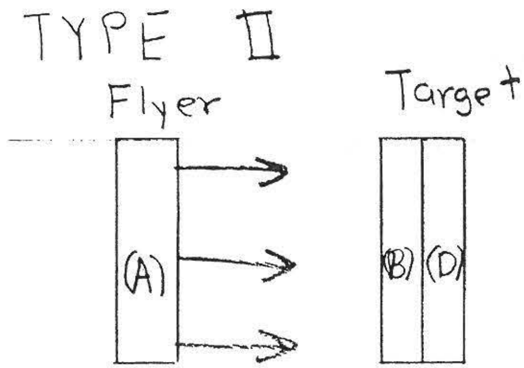
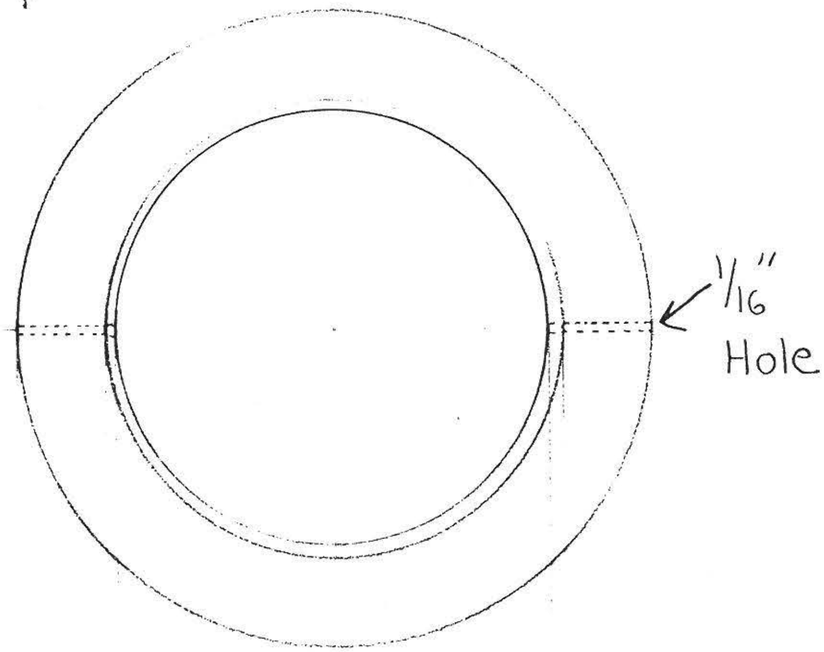


Fig. 1.1

TOLERANCES (EXCEPT AS NOTED)	Experimental Configurations		
DECIMAL ±		SCALE	DRAWN BY GTS APPROVED BY
FRACTIONAL ±	TITLE		
ANGULAR ±	DATE	DRAWING NUMBER	

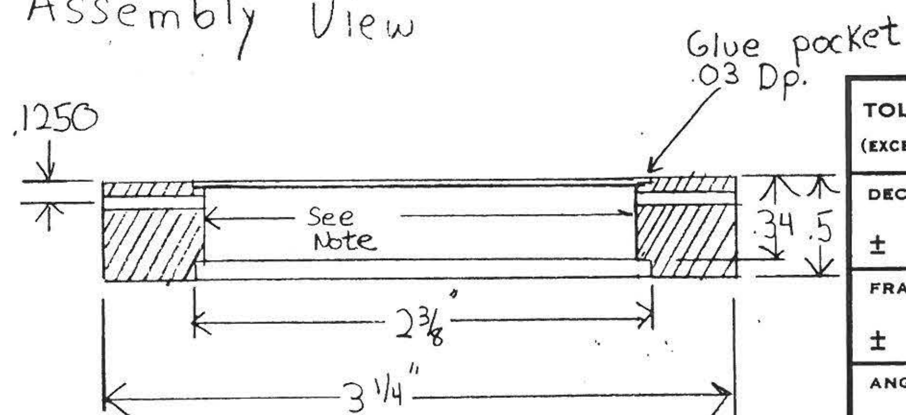
DATE	SYM	REVISION RECORD	AUTH.	DR.	CK.

Top View



Note- the cell diameter is such that the front & back windows (≈ 2.25" diameter) fit in cell with a light press fit,

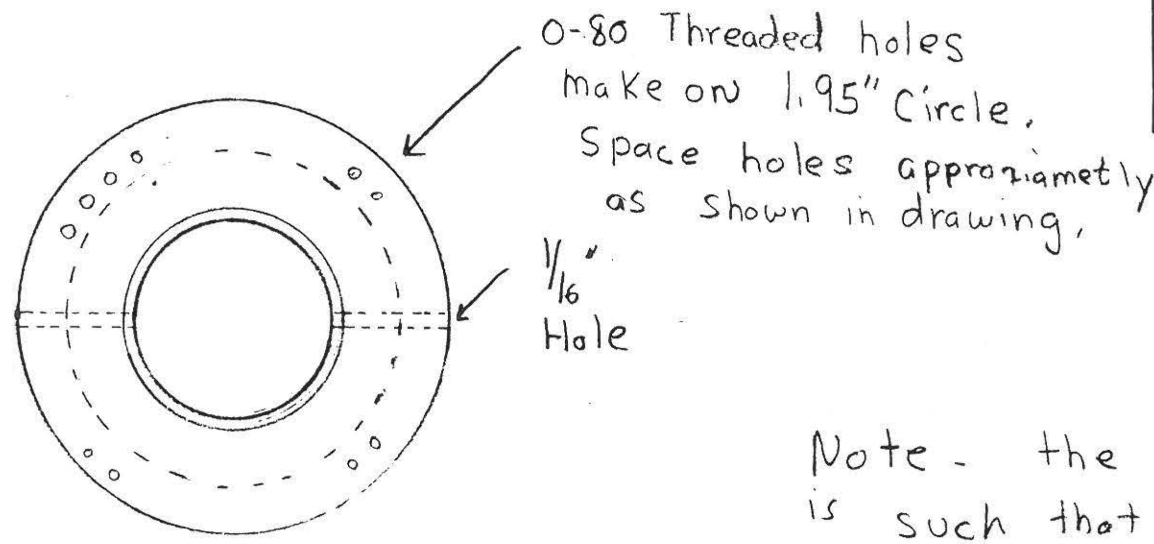
Assembly View



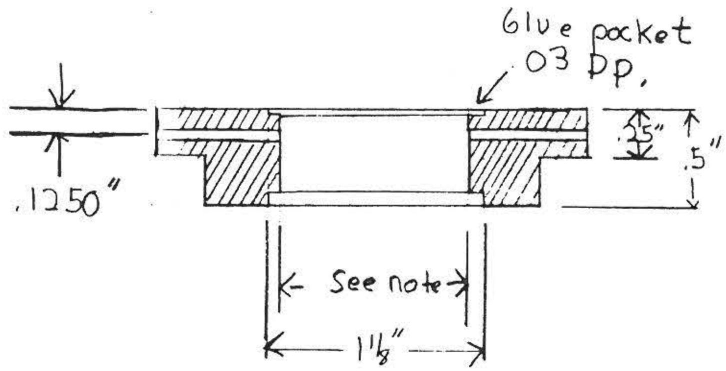
TOLERANCES (EXCEPT AS NOTED)	Cell Body (Large)			
DECIMAL ±	Make of PMMA □	SCALE 1-1	DRAWN BY GTS	
			APPROVED BY	
FRACTIONAL ±	TITLE			
ANGULAR ±	DATE	DRAWING NUMBER		

Fig. 1.2

DATE	SYM	REVISION RECORD	AUTH.	DR.	CK.



Note - the cell diameter is such that front & back windows (≈ 1" diameter) fit in cell with a light press fit.



TOLERANCES (EXCEPT AS NOTED)	Cell Body (Small)		
DECIMAL ±	Make of PMMA II	SCALE 1:1	DRAWN BY GTS / APPROVED BY
FRACTIONAL ±	TITLE		
ANGULAR ±	DATE	DRAWING NUMBER	

Fig. 1.3

because this material would not react with CS_2 and would not produce eddy currents in the presence of a magnetic field. Material disks B and D (see Fig. 1.1-III) were cemented into the cell with 815 epoxy. Two 1/16 inch O.D. diameter copper fill tubes were glued into the cell body to fill and flush the cell.

The small cell was made to hold 1 inch diameter pieces of random cut sapphire. Ten #0-80 brass screws were placed in holes drilled in the periphery of the cell body to serve as tilt and trigger pins.

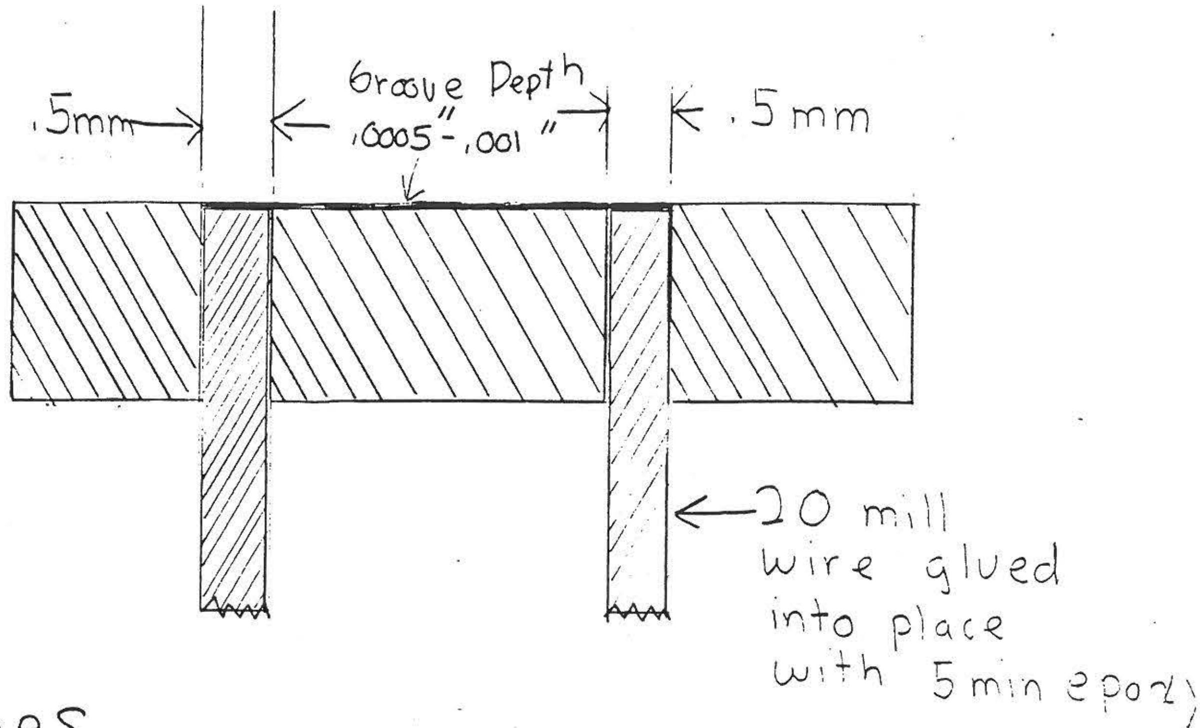
The large cell body was made to hold 2.25 inch diameter disks of Vistal [3], Z-cut sapphire and fused silica. The larger cell body offers several advantages with respect to the small cell body. Tilt strips can be deposited on material B meaning that the tilt measurements will be with respect to the impacted surface. A larger material disk diameters means more than one gauge can be used at a time.

Shim construction

Liquid layer thickness was determined by shims (0.996 inch O.D. by 0.875 inch I.D. and 2.245 inch O.D. by 2.000 inch I.D.) constructed out of nylon. Nylon was chosen because I thought I may be studying liquids which would dissolve a PMMA shim.

Gauge design

Electroplated Gauge



Foil Gauges

Type I

Type II

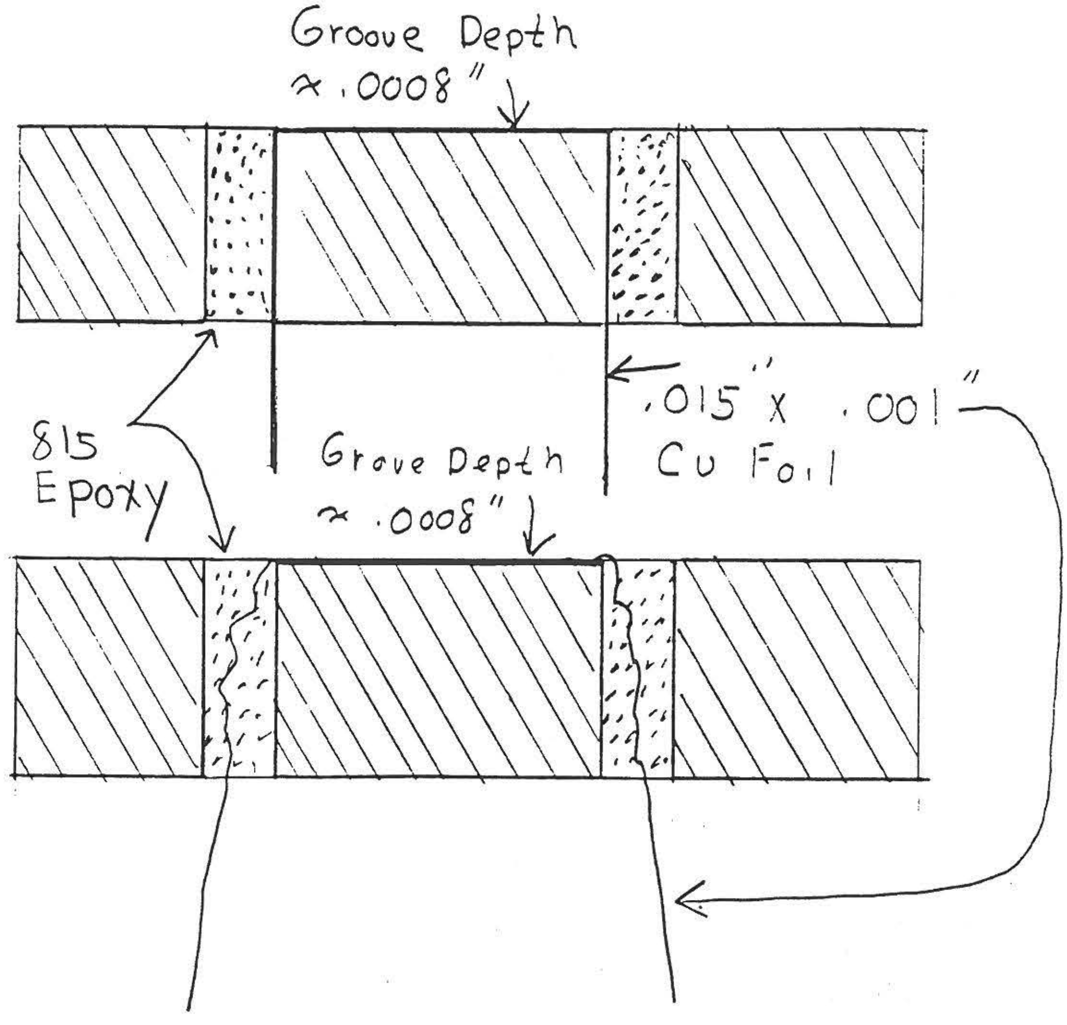


Fig. 1.4

The two types of gauges used in reverberation experiments are illustrated in Fig. 1.4.

The plating procedure for electroplated gauges was as follows. The copper posts were trimmed with a razor blade until level with the bottom of the groove. The groove was throughly cleaned. A thin nichrome layer was vapor deposited in the groove followed by a thin copper layer. The groove was filled with copper by electroplating. The plating was then sanded until flush with the substrate surface [4].

The foil gauges were constructed by pressing the substrate (with foil laid in glued filled holes and groove) onto a piece of Teflon film. After the glue dryed, the film was removed from the substrate and the foil sanded flush with respect to the substrate surface. Two gauge types were constructed: one in which the foil was pulled snug against the holes (type I) and one type in which no effort was made to snug the foil.

Data analysis

The program used to reduce the data is very similar to the program described in Ref. 5.

The U-u relationships, used in the SHOCKUP calculation [6], for Vistal [3], random cut sapphire and Z-cut sapphire are given by

$$U = C_0 + 1.0\,u \qquad (1.1)$$

where C_0 is the sound speed, U is the shock speed and u is the particle velocity. The sound speeds were measured for each piece of random cut sapphire. The sound speed of Z-cut sapphire was taken to be 11.19 mm/usec; the sound speed of Vistal [3] was taken to be 10.79 mm/usec. The density of all three materials was taken to be 3.985 gr/cc. The density and stress-strain relationships for fused silica were taken from Barker and Hollenbach [7]. The response of CS2 will be given by Sheffield's second equation of state [8]. The response of PMMA II will be given in Chapter 3.

Experimental plan

Two initial reverberation experiments were performed in which electroplated gauges were used. Shot 85-540 was a "dropped experiment" in that only base lines were obtained. Shot 85-542 yielded a strange voltage-time record which showed little correlation with SHOCKUP calculations. At this time, I have little explanation regarding the results of this shot.

Three experiments were proposed to see if results of shot 85-542 were due to a gauge or fluid effect. Foil gauges were used to reduce the substantial labor involved in constructing electroplated gauges. I errored in making the gauges for experiments 85-554 and 85-557 in configuration II (see Fig. 1.4). This error was found just after gauge construction. It was decided that this would give a substantial uncertainty in gauge length but since the shots were diagnostic shots to live with this uncertainty. I regret this decision. Three experimental configurations were constructed: a shot in which PMMA was used as material C (see Fig. 1.1-III); a thick CS2 layer shot; and a thin CS2 layer experiment. The PMMA (S85-554) and thick CS2 cell (S85-557) experiments were performed and results did not agree with results predicted from SHOCKUP calculations. The conclusion was that the poor gauge response was due to the gauges themselves. The thin cell experiment was constructed but not shot.

A symmetric impact experiment S85-558 was performed to test the response of the two configurations of foil gauges. Foil gauges of type I (see Fig 1.4) in a fused silica matrix performed very well.

A reverberation experiment was performed (S85-563) in which two foil gauges were embedded in material D (fused silica, see Fig. 1.1-III). The results, although obscured by an operator error of chosing too thin of impactor, gave encouraging results.

Another reverberation experiment (S85-567) was performed. A foil and a electroplated gauge were embedded in Vistal [3]. This experiment gave encouraging results.

Chapter 2

Shot 85-542

Objective

To measure the particle velocity-time profile at the back surface of a cell containing CS2.

Comments

An electroplated gauge was centered in the back sapphire piece.

Conclusions

From looking at the pressure-time profiles (Figs. 2.1 and 2.2) one can see that little correlation exists with the SHOCKUP calculation (Fig. 2.3). Disturbing is the magnitude of the first spike shown in the profiles. I find it hard to believe that a bad copper and chrome vapor deposition layer could cause such a large amplitude spike. In hindsight, I would have likely performed a symmetric impact experiment with electroplated gauges in sapphire after getting this experimental result. At this time, I can form no conclusions from the strange profiles recorded.

hot 85-542

ate 8 May85

rojectile vel. - 0.524 mm/usec

alculated pressure of steps - 35.4, 80.2, 105.1, 114.7 and

18.0 kilobar

agnetic Field - 2834 guass

auge length - 6.492

auge resistance - 0.04 ohms

roove depth - 25-29 um

ilt 1.1 mrad

lyer material - Z-Cut Sapphire

arget configuration (see Fig. 1) III

arget material (front layer) - Random Cut Sapphire

h kness - 3.150 mm

ound Speed 11.40 mm/usec

arget material (second layer) - CS2

hickness - 254 microns (shim thickness) 255 (measured)

arget material (third layer) - Random Cut Sapphire

hickness - 6.353 mm

ound Speed 11.24 mm/usec

omputer file location of records

pper/Srecords/S85-542

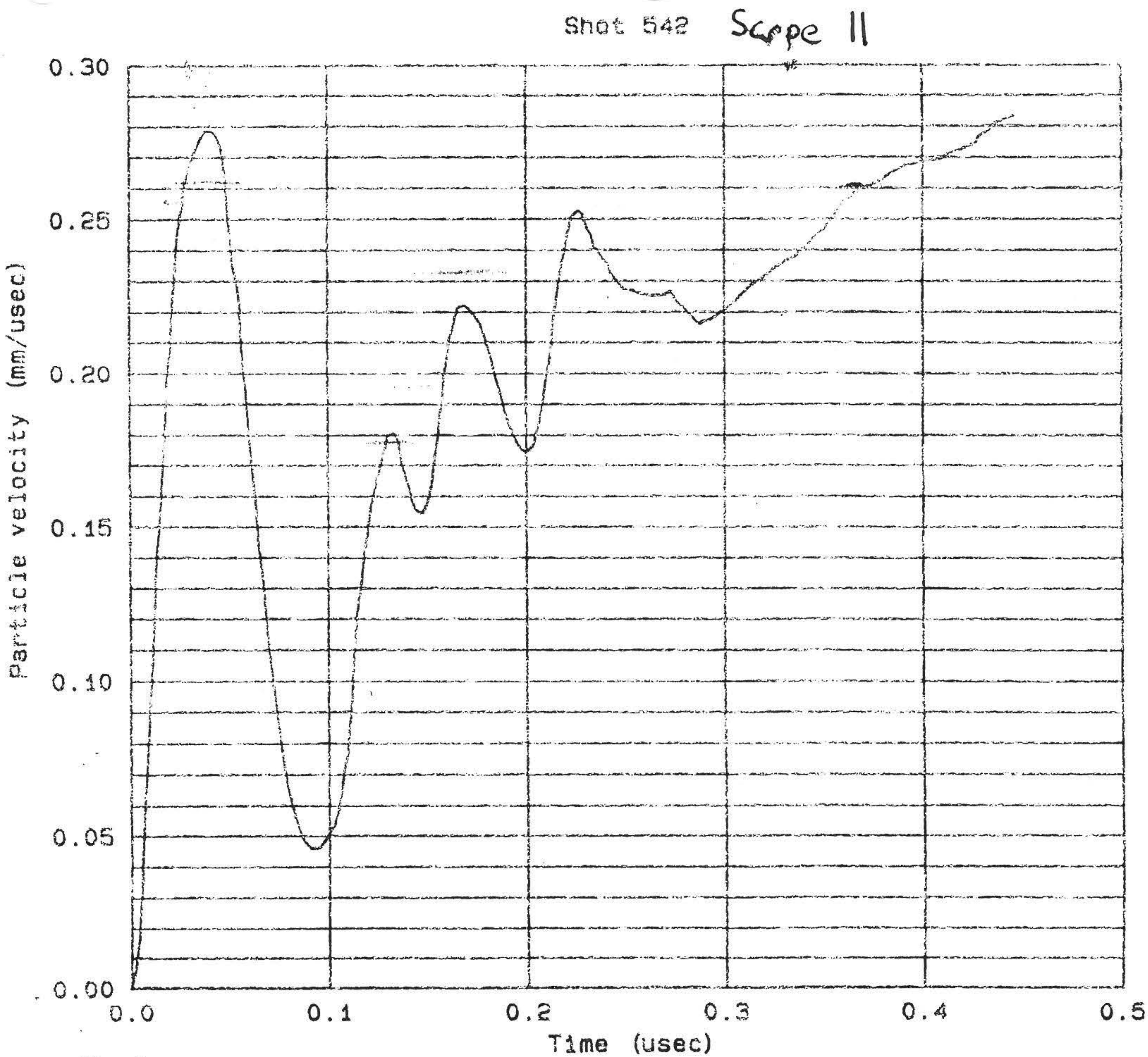

Shot 542 Scope II
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Particle velocity (mm/usec)
0.0
0.1
0.2
0.3
0.4
0.5
Time (usec)

Fig. 2.1

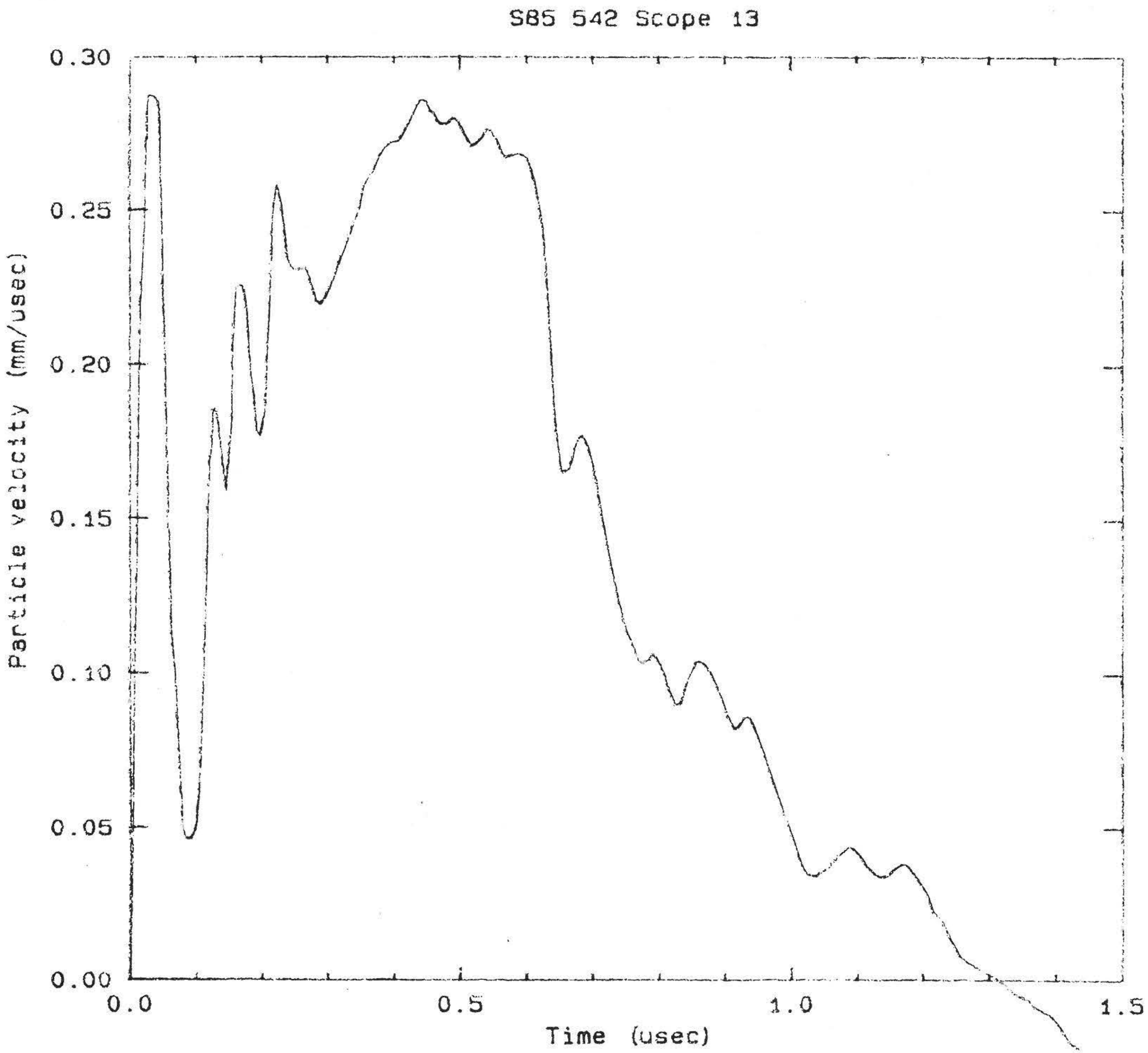

S85 542 Scope 13
Particle velocity (mm/usec)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
Time (usec)

Fig. 2.2

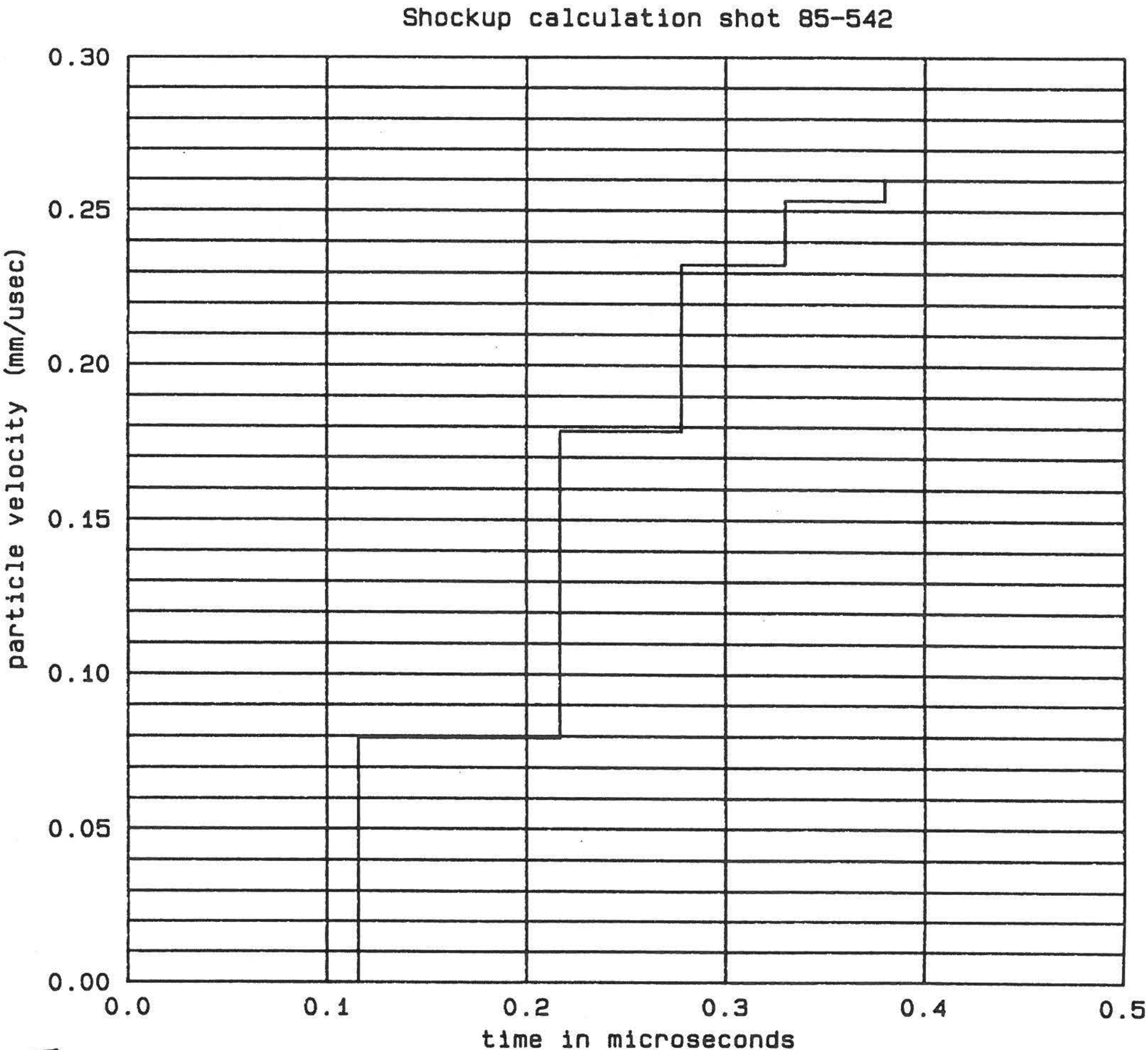

Shockup calculation shot 85-542
particle velocity (mm/usec)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.1
0.2
0.3
0.4
0.5
time in microseconds

Fig. 2.3

S 85-42
Scope Setup

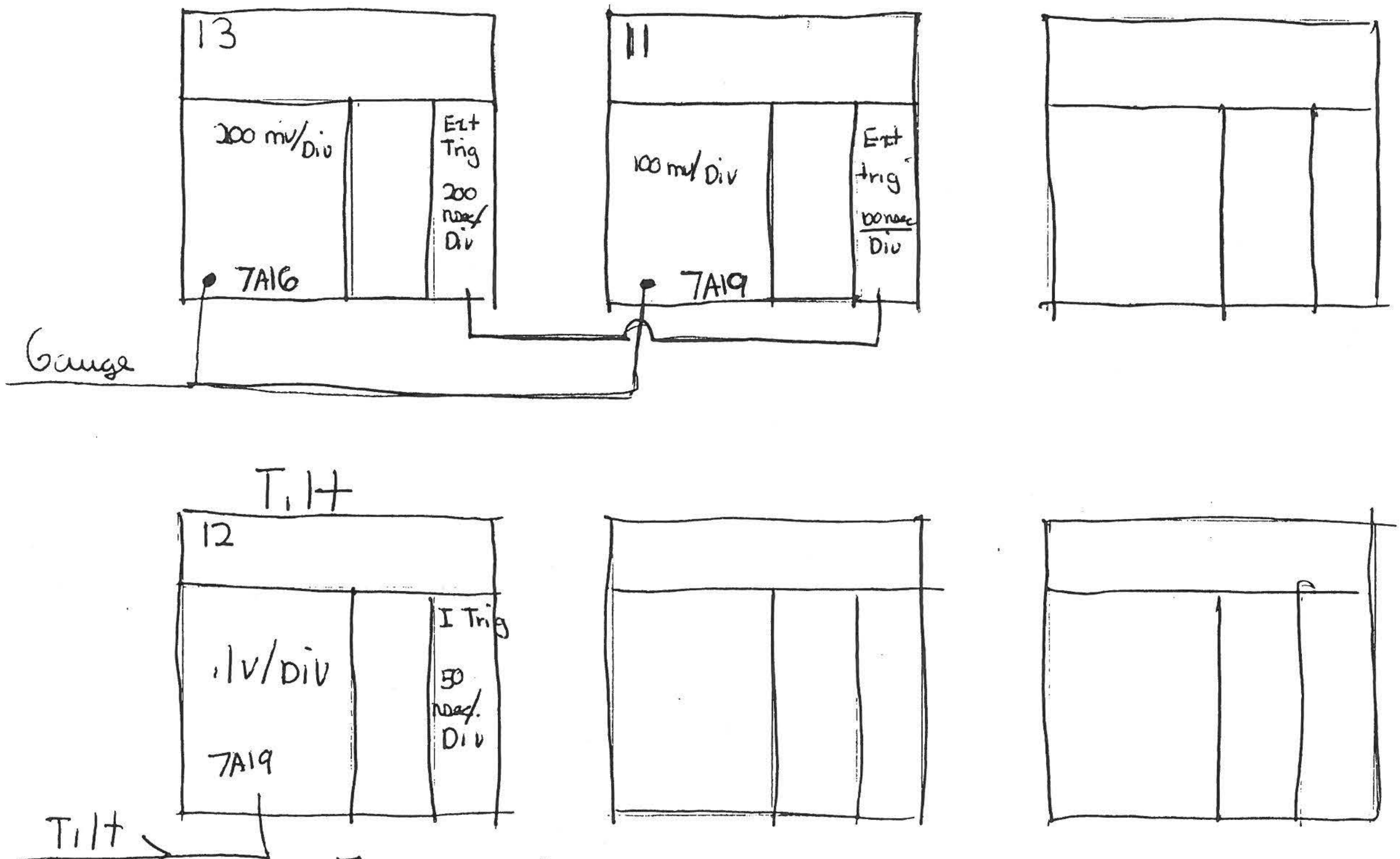


Fig. 2.4

Chapter 3

Shot 85-554

3.23 mm/μsec

Objective

To see if results observed in S85-542 were due to a fluid or gauge effect. The thin layer of PMMA being shocked would insure that a known thickness layer of low impedance material was being shocked. A slight possibility existed in Shot 85-542 that some of the liquid could not have been present in the cell at the time of the experiment.

Comments

A foil gauge of type II (see Fig. 1.4) was used. I regret that I did not take the time to reconfigure the gauge into a type I gauge. It was decided that the diagnostic nature of this shot did not warrant the gauge reconfiguration.

A linear U-u relation was used in the SHOCKUP calculations to describe the PMMA

$$U = .272 \frac{cm}{\mu sec} + 1.454\,u \qquad (3.1)$$

where U is the shock speed and u the particle velocity. The density of PMMA was taken to be 1.186 gr/cc.

Inspecting the scope set up sheet (Fig. 3.1) one sees that a power divider was used in this experiment.

The length of type II foil gauges could vary during the time of the experiment; pressure- time profiles assuming maximum and minimum possible gauge lengths were hence plotted (Figs. 3.2,3.4 and 3.5).

The voltage record recorded by scope 11 went off scale about .35 microseconds into the experiment. Protective zenor diodes in the 7A19 plugin of this scope were tripped; the voltage-time profile of scope 13 was thus affected .6 microseconds into the experiment.

Conclusions

Assuming a maximum gauge length, one can see that the SHOCKUP calculation (Figs. 3.2 and 3.3) experimental profiles show some agreement for the first two pressure steps. I have not checked the accuracy of the Hugoniot given above for PMMA.

Very disturbing is the fact that the particle velocity recorded is over one half the projectile velocity even assuming a maximum gauge length. I strongly object to the premise that the results observed were due to improper use of a power divider. I conjecture that results were due to a lead effect; the foil leads were placed in holes filed with low impedance glue surrounded by a high shock impedance material (see Fig. 1.4).

:h ` 85-554

)ate 6 June85

'rojectile vel. - 0.544 mm/usec

:alculated pressure of steps 43.4, 83.5, 106.7, 117.2, and

.22.7 kbar

lagnetic Field - 2912 guass

;auge length - 5.924 to 6.948 mm

;auge resistance - 0.06 ohms

;roove depth - 12-21 um

:ilt .3 mrad

'lyer material - Z-Cut Sapphire

:arget configuration (see Fig. 1) III

:arget material (front layer) - Random Cut Sapphire

:h kness - 3.165 mm

;ound Speed 11.32 mm/usec

:arget material (second layer) - PMMA II

:hickness - 258 microns (PMMA thickness) 255 (measured)

:arget material (third layer) - Random Cut Sapphire

:hickness - 6.353 mm

;ound Speed 11.26 mm/usec

:omputer file location of records

ıpper/Srecords/S85-554

S 85-554
Scope Setup

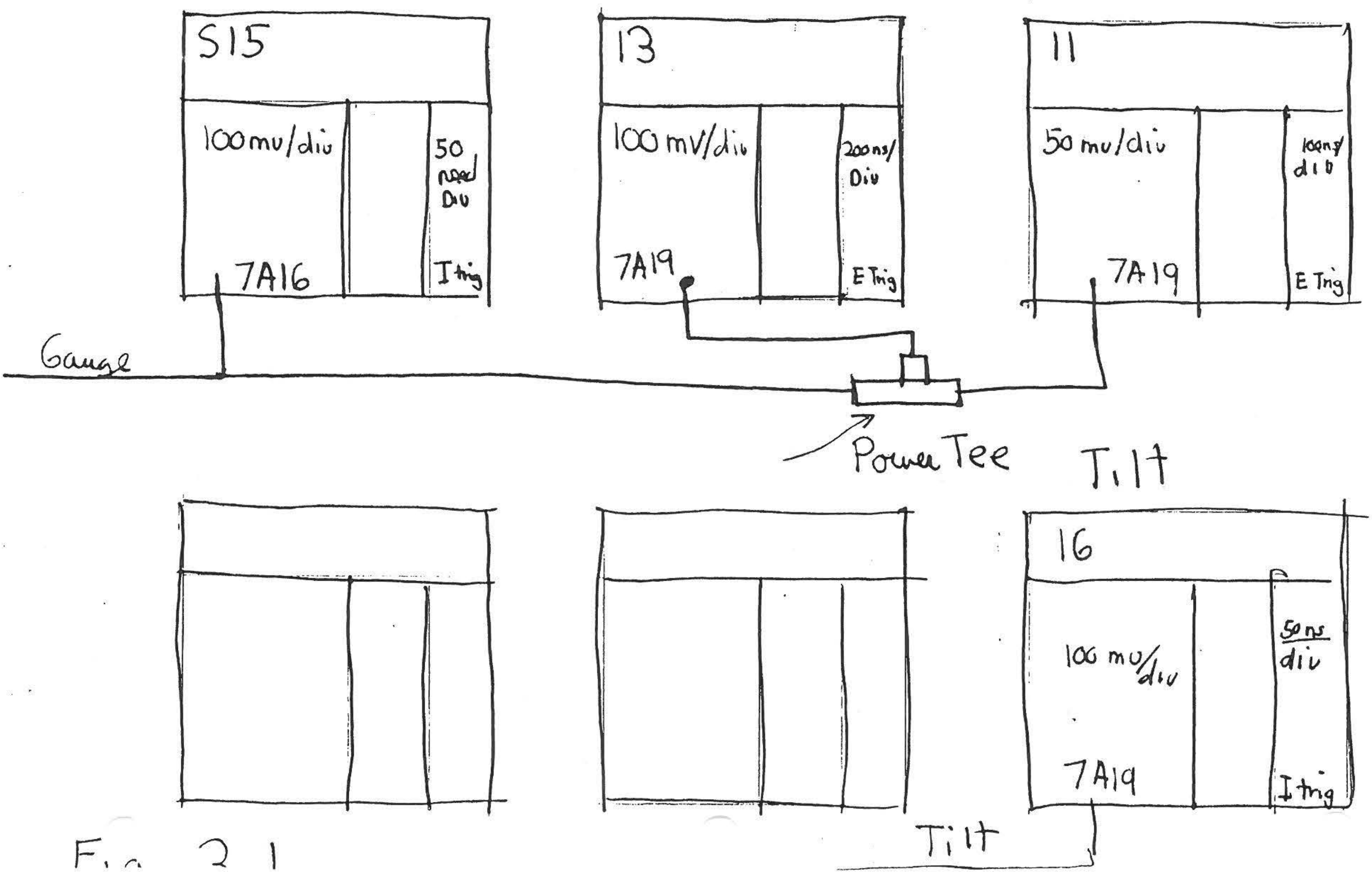


Fig. 21

S85-554 Scope 11

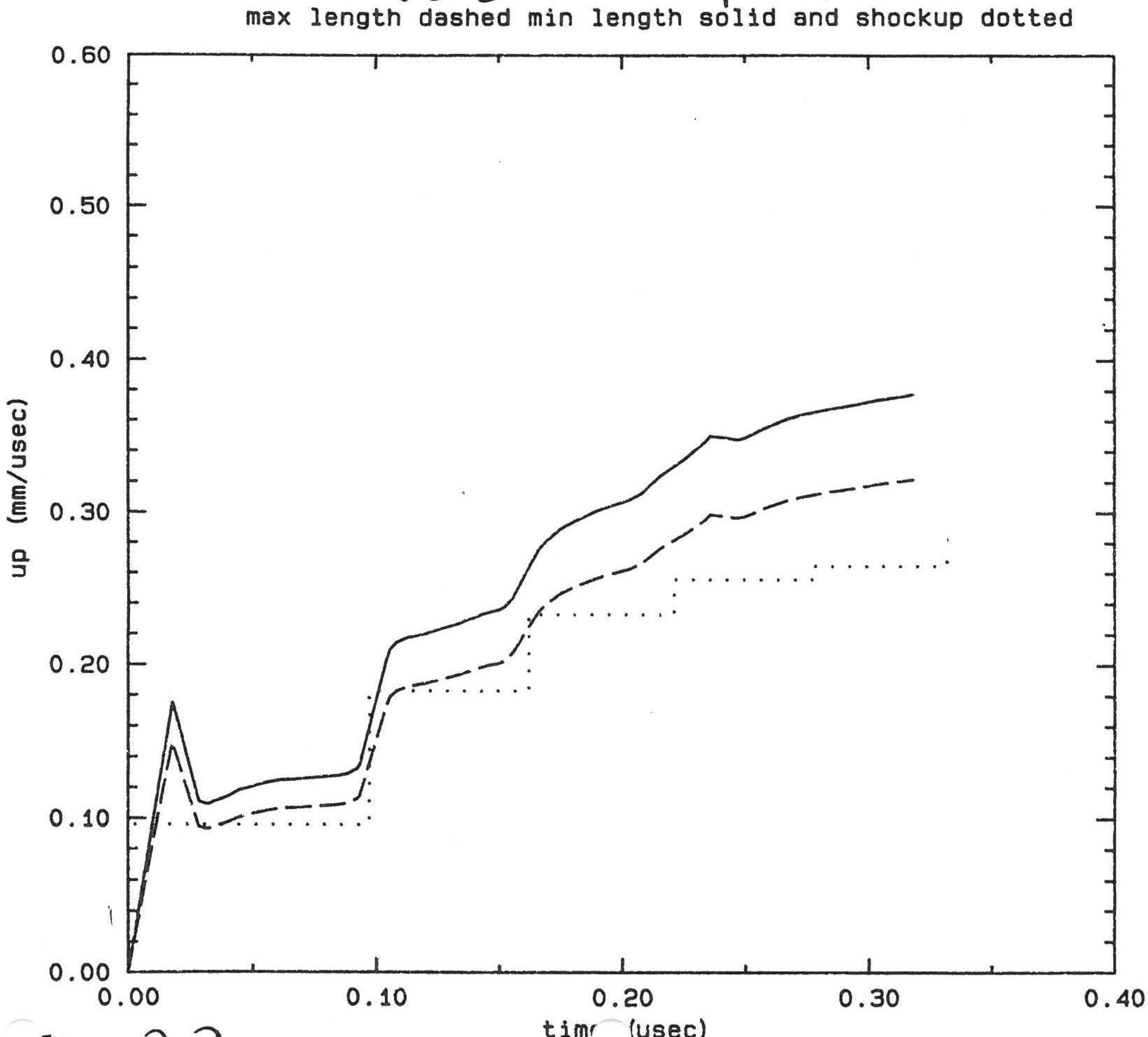


Fig. 3.7

23

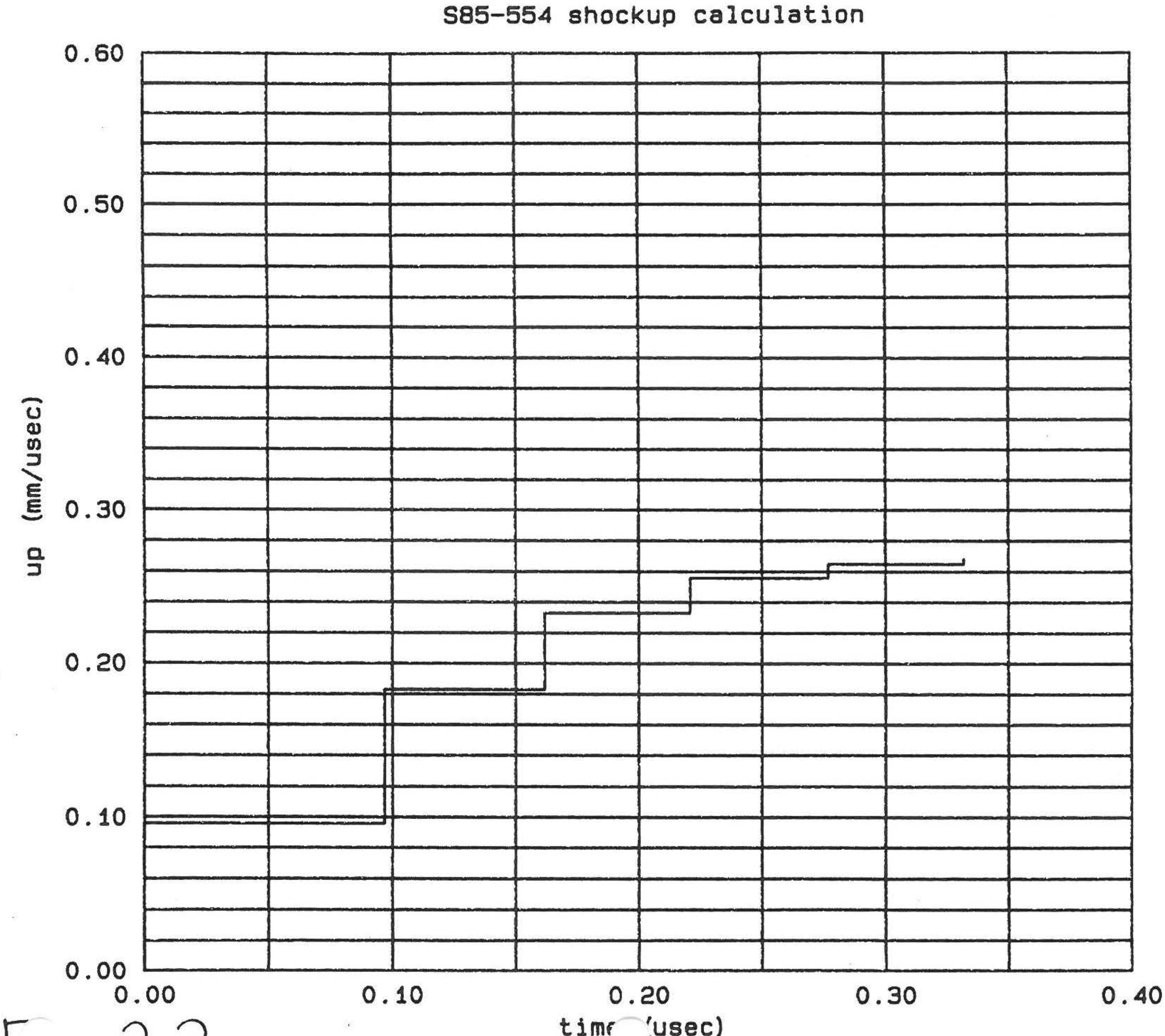

S85-554 shockup calculation
0.60
0.50
0.40
0.30
0.20
0.10
0.00
up (mm/usec)
0.00
0.10
0.20
0.30
0.40
time (usec)

Fig. 3.3

24

S85-554 Scope 13

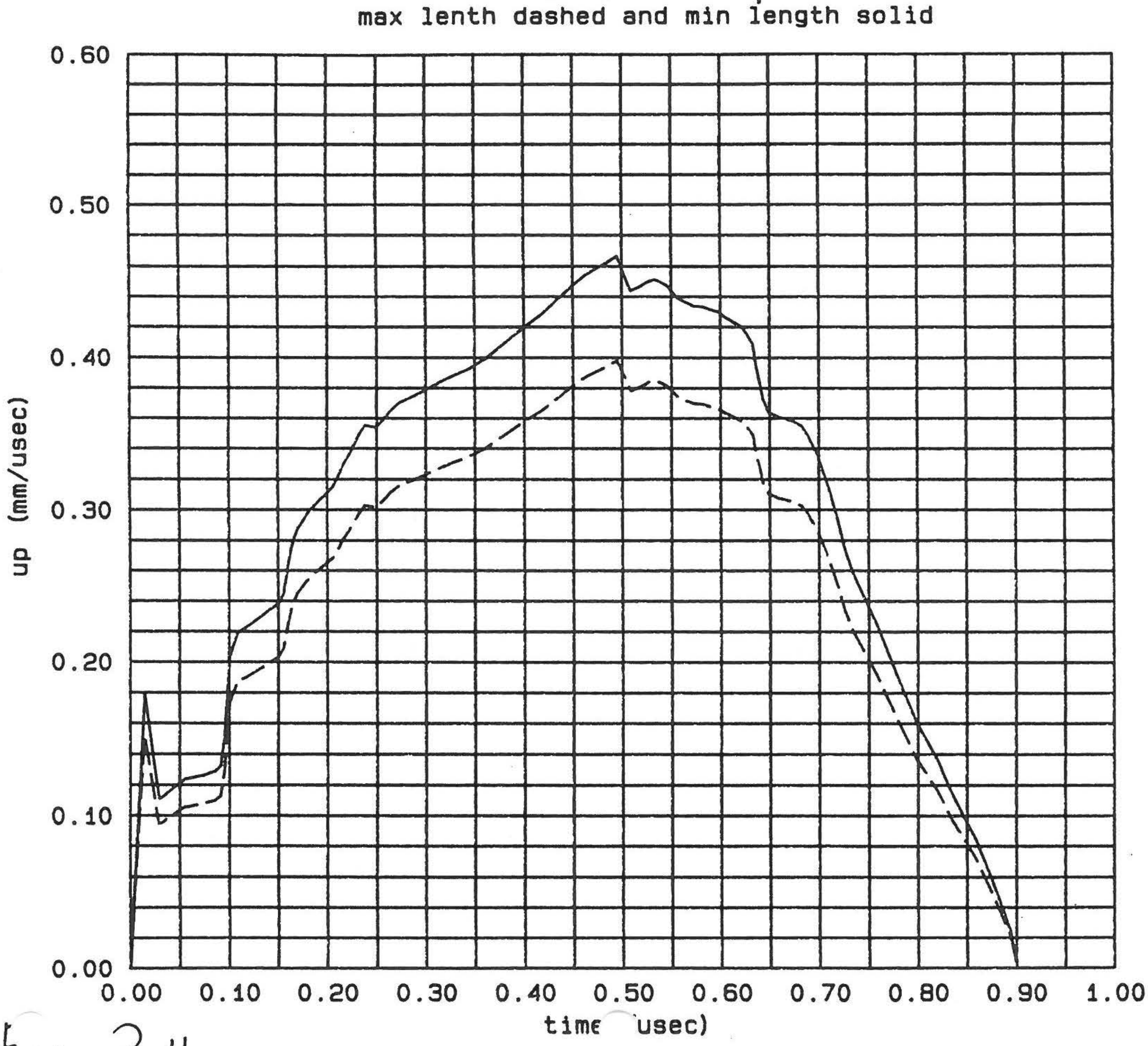


Fig 3.4

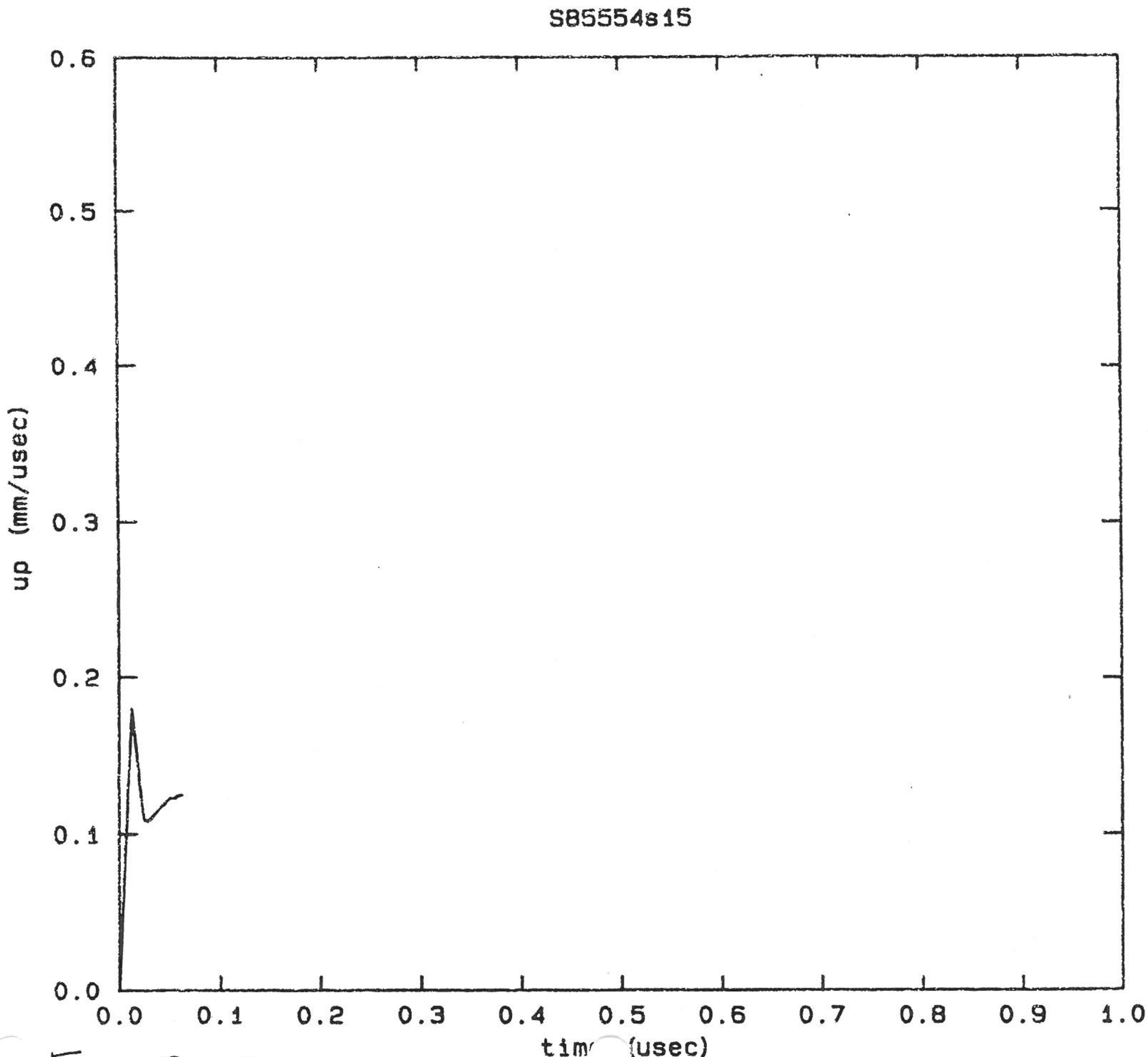

S85554s15
up (mm/usec)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
tim (usec)

Fig 3c

Chapter 4

Shot 85-557

Objective

To measure the particle velocity of a single shock propagated into a thick CS2 layer. To see if the results observed in shot 85-557 were due to a gauge or fluid effect.

Comments

A foil gauge of configuration II was used (see Fig. 1.4).

The internally triggered scope did not trigger properly (Fig. 1.4).

The length of type II foil gauges could vary during the time of the experiment; pressure- time profiles assuming maximum and minimum possible gauge lengths were hence plotted.

Conclusions

The profiles observed (Fig. 4.2) and SHOCKUP calculation loose any correlation after 0.1 microsecond. I surmise that it is a lead effect which is causing the ramping in the particle velocity profiles observed.

The sudden drop in particle velocity observed .35 microseconds into the experiment could be caused by the gauge breaking.

85-557

ate 14 June85

rojectile vel. - 0.545 mm/usec

alculated pressure of step - 37.4 kbar

agnetic Field - 2886 guass

auge length - 6.008 to 7.096 mm

auge resistance - 0.07 ohms

rove depth - 18-20 um

ilt - .9 mrad

lyer material - Z-Cut Sapphire

arget configuration (see Fig. 1) III

arget material (front layer) - Random Cut Sapphire

hickness - 3.150 mm

d Speed 11.44 mm/usec

arget material (second layer) - Carbon Disulfide

hickness - 1550 microns (shim thickness)

arget material (third layer) - Random Cut Sapphire

hickness - 6.307 mm

ound Speed 11.05 mm/usec

omputer file location of records

pper/Srecords/S85-557

S 85-551

Scope Setup

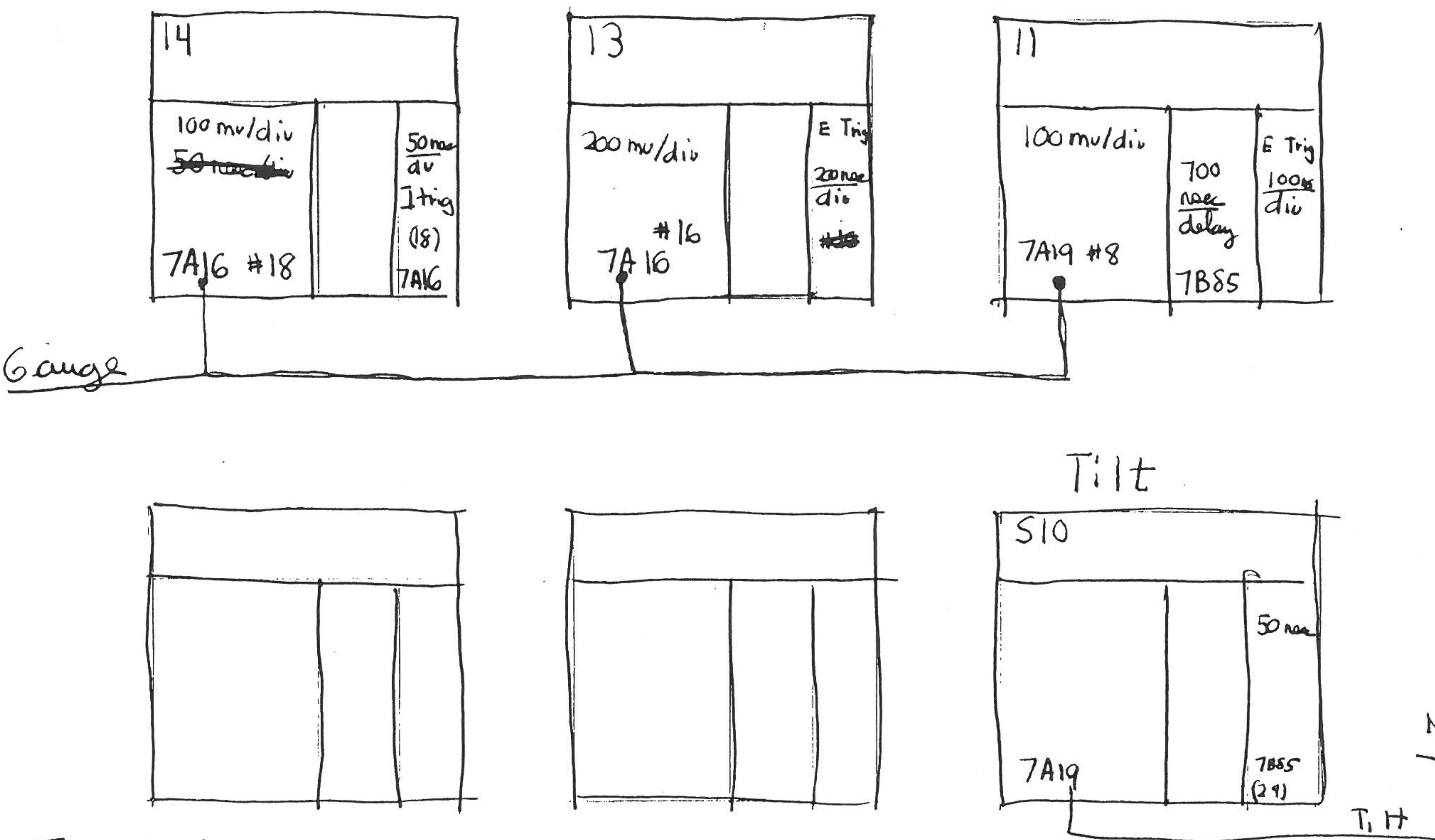


Fig. 4.1

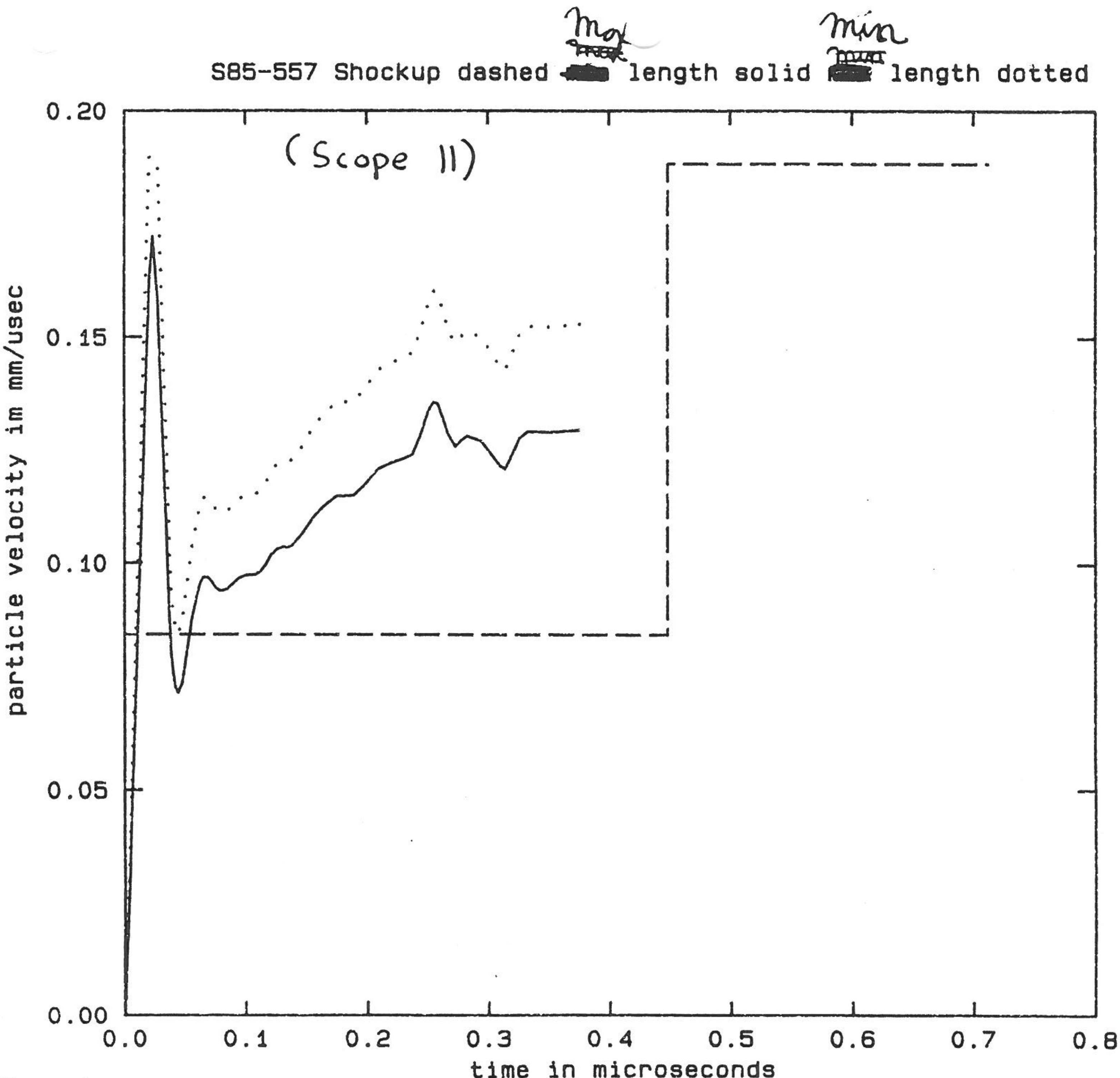

Max
min
S85-557 Shockup dashed [redacted] length solid [redacted] length dotted
(Scope 11)
particle velocity im mm/usec
0.20
0.15
0.10
0.05
0.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
time in microseconds

Fig 4.2

Chapter 5

Shot 85-558

Objective

To compare the performance of type I and type II foil gauges in a fused silica matrix in a symmetric impact experiment.

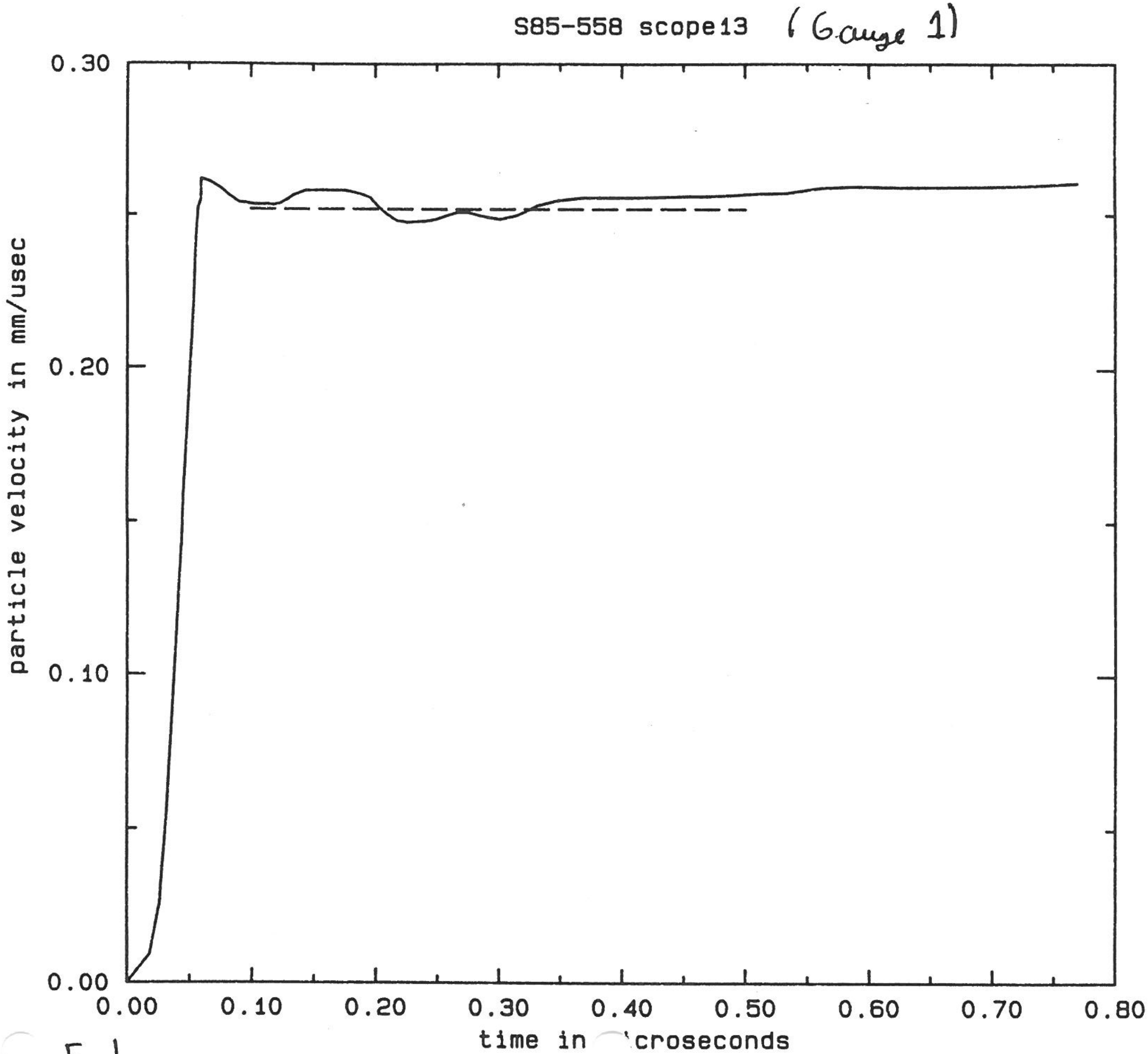
Comments

Gauge 1 was of type I; Gauge 2 was of type II (see Fig 1.4).

Gauge 2 profiles were plotted (Figs. 5.2 and 5.4) assuming minimum and maximum gauge lengths. Shown on profiles is a line representing one half the projectile velocity.

Conclusions

Type I gauges gave good performance. Absent from experimental profiles are indications of the large particle velocity spikes recorded in earlier profiles. The type I gauge measured a profile that is very close to profiles predicted by Barker and Hollenbach [7]. The effective length of the type II gauge seemed to stay fairly constant over 700 nanoseconds. I would conclude that type I foil gauges would perform well in a fused silica matrix.


S85-558 scope13 (Gauge 1)
particle velocity in mm/usec
0.00
0.10
0.20
0.30
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
time in 'croseconds

Fi 5.1

S' . 85-558

)ate 21 June85

?rojectile vel. - 0.504 mm/usec

Magnetic Field - 2872 guass

Gauge 1 length - 5.971 mm

Gauge 1 resistance - 0.10 ohms

Gauge 2 length - 5.928 to 7.126 mm

Gauge 2 resistance - 0.09 ohms

Tilt - tilt measurement failed

Flyer material - Fused Quartz

Target configuration (see Fig. 1) II

Thickness - 3.188 mm

Target material (front layer) - Fused Quartz

Th ckness - 1.036 mm

Target material (second layer) - Fused Silica

Thickness - 6.350 mm

Computer file location of records

ıpper/Srecords/S85-558

s85-558 scope11 (Gauge 1)

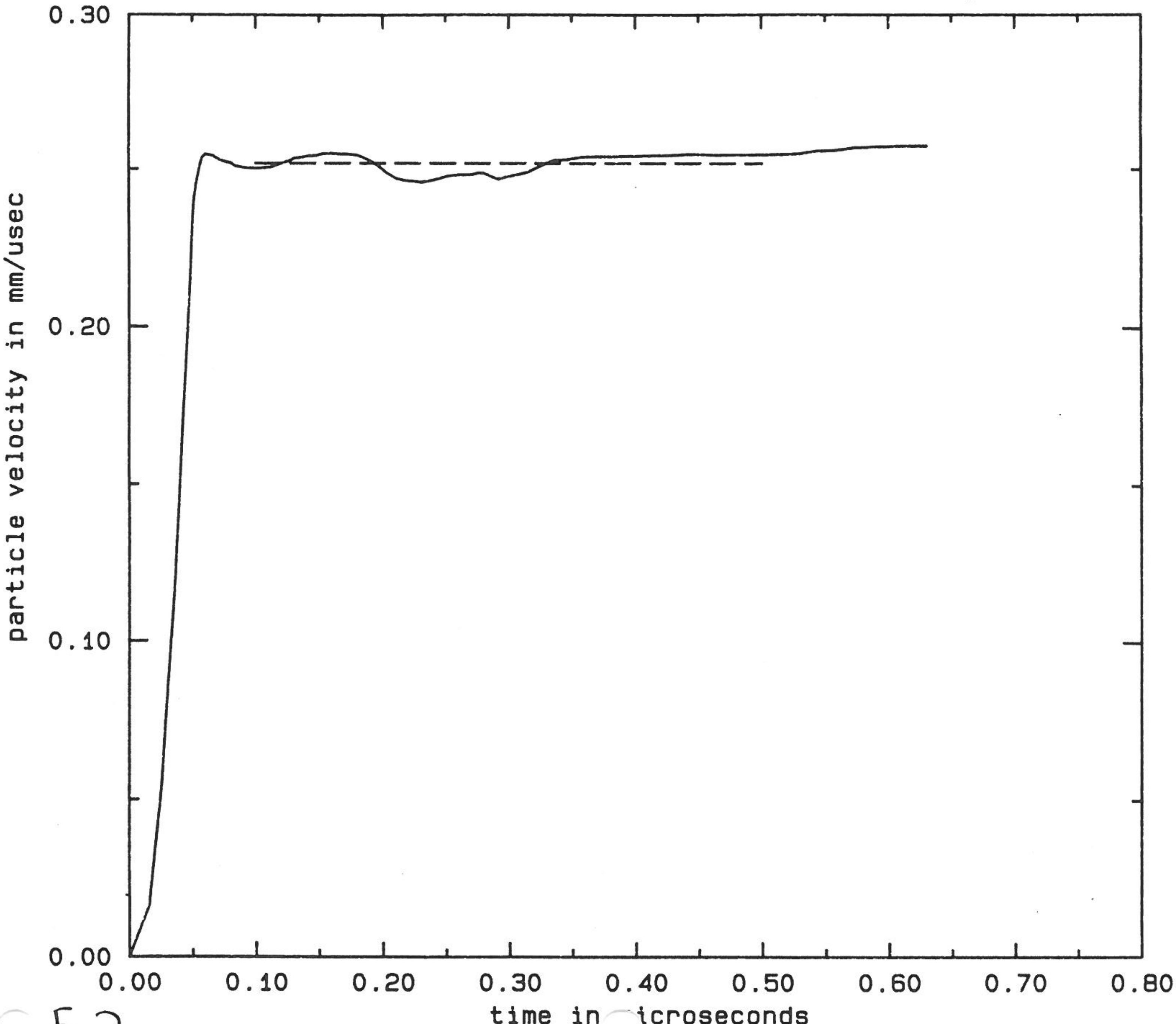


Fig 5.2

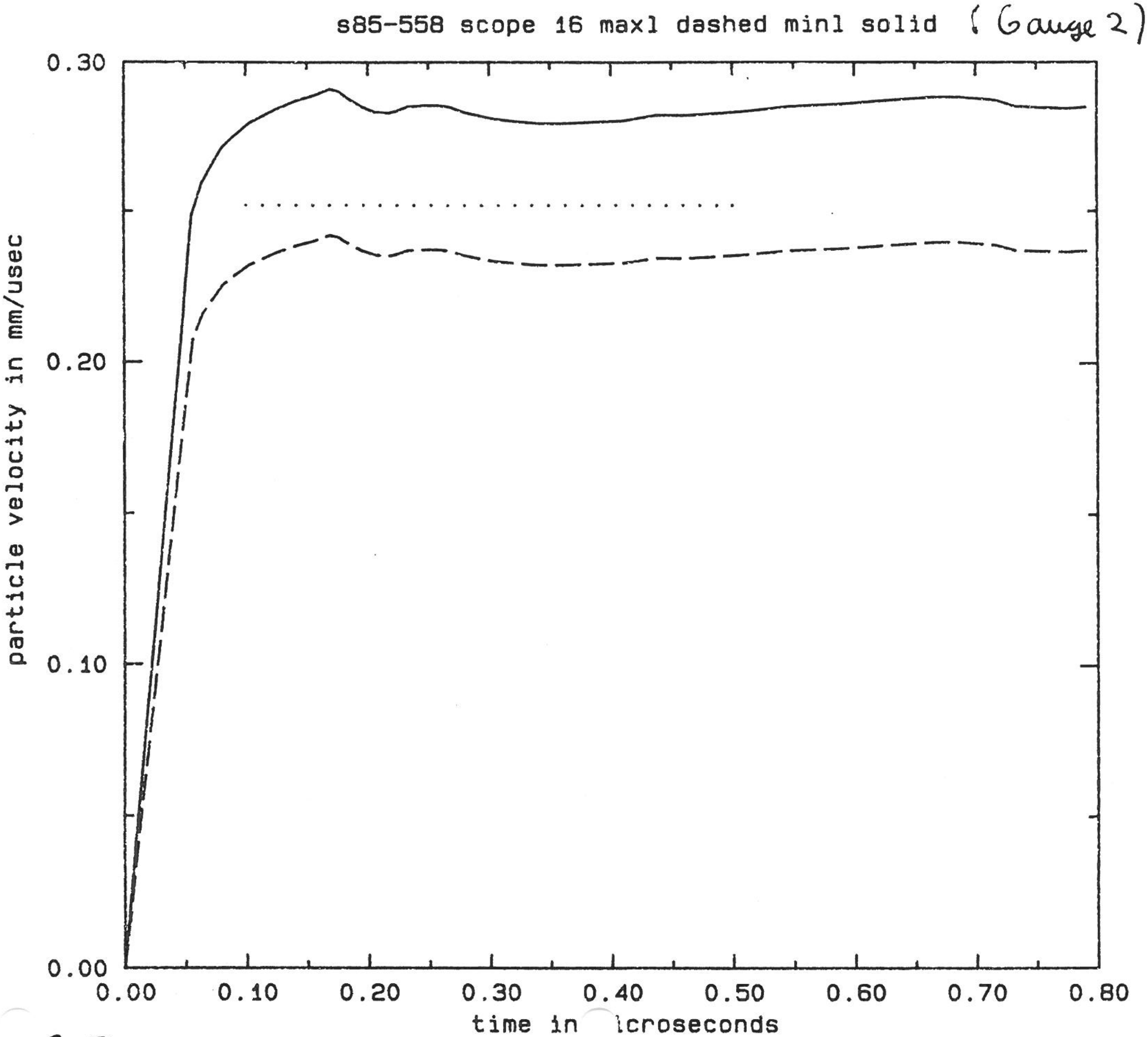

s85-558 scope 16 max1 dashed min1 solid (Gauge 2)
particle velocity in mm/usec
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
time in icroseconds

Fig E 2

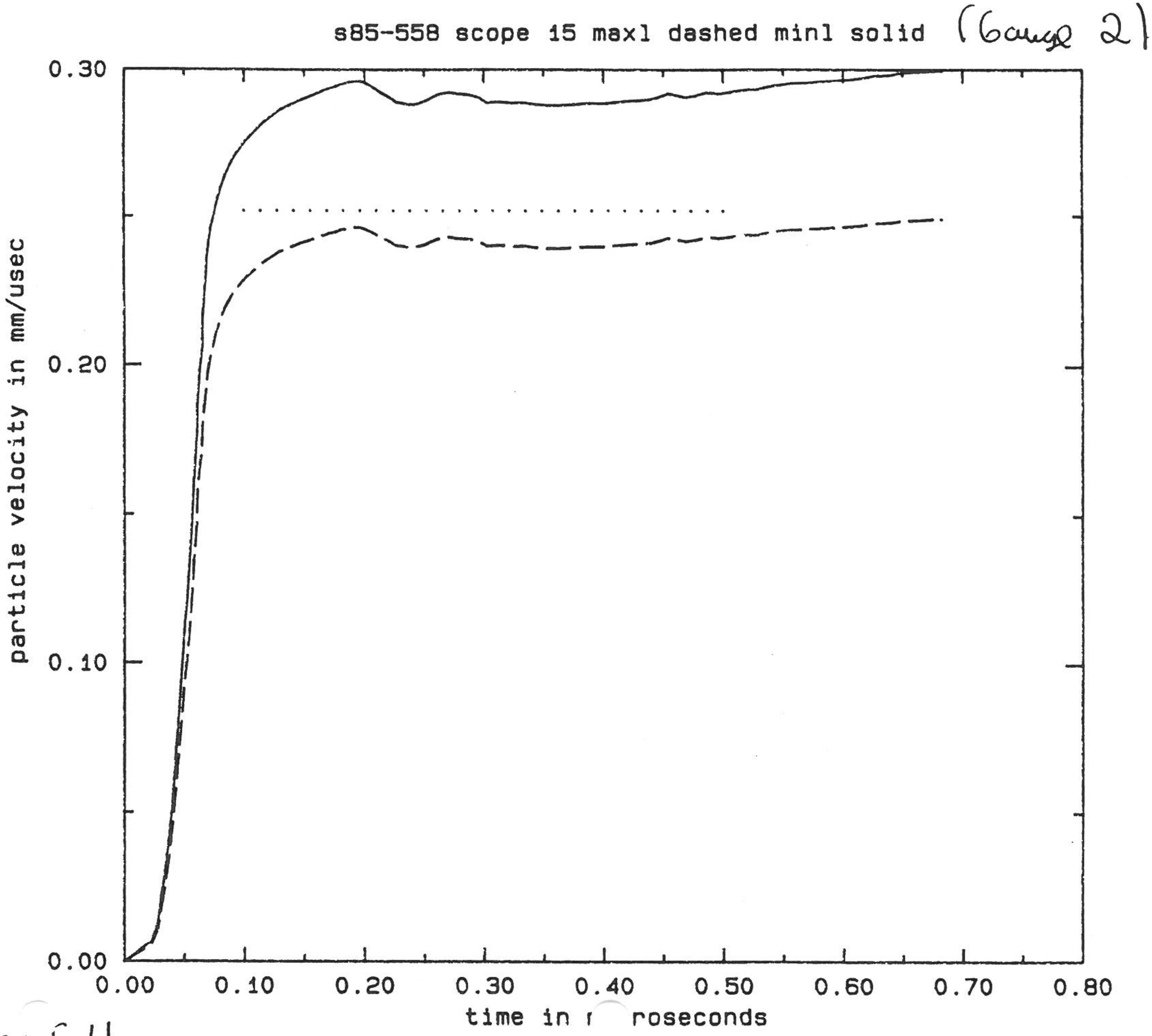
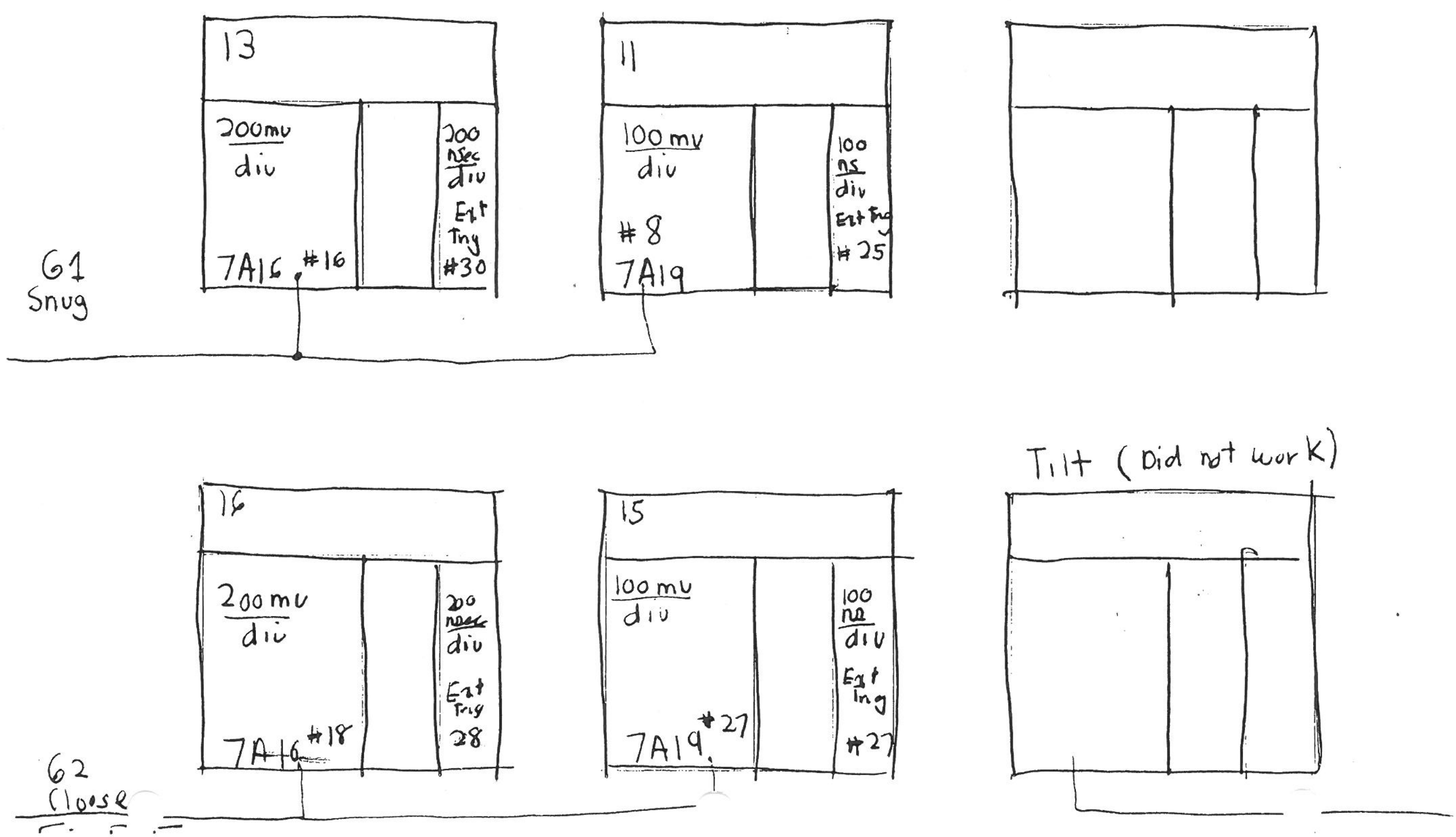

s85-558 scope 15 max1 dashed min1 solid
(Gauge 2)
particle velocity in mm/usec
0.00
0.10
0.20
0.30
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
time in roseconds

Fig 5.4

S 85-558
Scope Setup



Chapter 6

Shot 85-563

Objective

To measure the particle velocity-time profile of a thin layer of CS2 with a back cell material of fused silica.

Comments

Two type I foil gauges were used. Gauge 2 was constructed with holes filled with increased impedance glue. Epon 815 glue impedance was increased by 70% by the addition of extremely fine alumina powder. Gauge 1 was constructed with holes filled with Epon 815 glue (see Fig. 1.4).

Fused silica was chosen for the back material to give a longer experiment recording time and because foil gauges should perform better when placed in a lower impedance material. Vistal [3] was chosen as the impactor and front face because it is inexpensive and has very good flatness and parallelism characteristics.

An error was made by the experimenter, I made the impactor out an 1/8 inch thick piece of Vistal instead of a 1/4 inch piece. This error allowed only two pressure steps to be measured. The moral of the story is to always construct x-t diagrams no matter how rushed you are.

Conclusions

Comparison of gauge 1 and gauge 2 experiment profiles (Figs 6.1–6.4) leads to the conclusion that how a foil gauge is made leads to great differences in how it performs. The difference in gauge response is probably due to differences in the thickness of glue under the foils which are laid in the grooves. The glue thickness under gauge 1 could have been greater than under gauge 2 because the groove depth was greater than the thickness of the foil. Both gauges showed little indication of voltage ramping, indicating no improved performance due to the higher impedance glue in the holes of gauge 2.

The dip in step 2 is due to a release wave comming from the front impactor (see comments).

Good agreement was found with the SHOCKUP calculation for step 1, the SHOCKUP calculation predicted higher particle velocity values for step 2 however.

hot 85-563

a.. 2 July85

rojectile vel. - 0.405 mm/usec

alculated pressure of steps 19.1, 33.0 and 36.9 kilobar

:agnetic Field - 2874 guass

auge 1 length - 9.704 mm

auge 1 resistance - 0.09 ohms

rove dept (G1) - 33-35 um

auge 2 length - 9.686 mm (foil)

auge 2 resistance - 0.10 ohms

roove depth (G2) 25-30um

ilt - 0.8 mrad

lyer material - Vistal

a et configuration (see Fig. 1) III

arget material (front layer) - Vistal

hickness - 3.187 mm

arget material (second layer) - Carbon Disulfide

hickness - 502 microns (measured) 511 microns (shim thick-
ness)

arget material (third layer) - Fused Quartz

hickness - 6.365 mm

omputer file location of records

ipper/Srecords/S85-563

S85-563 scope 13 and shockup calculation (G1)

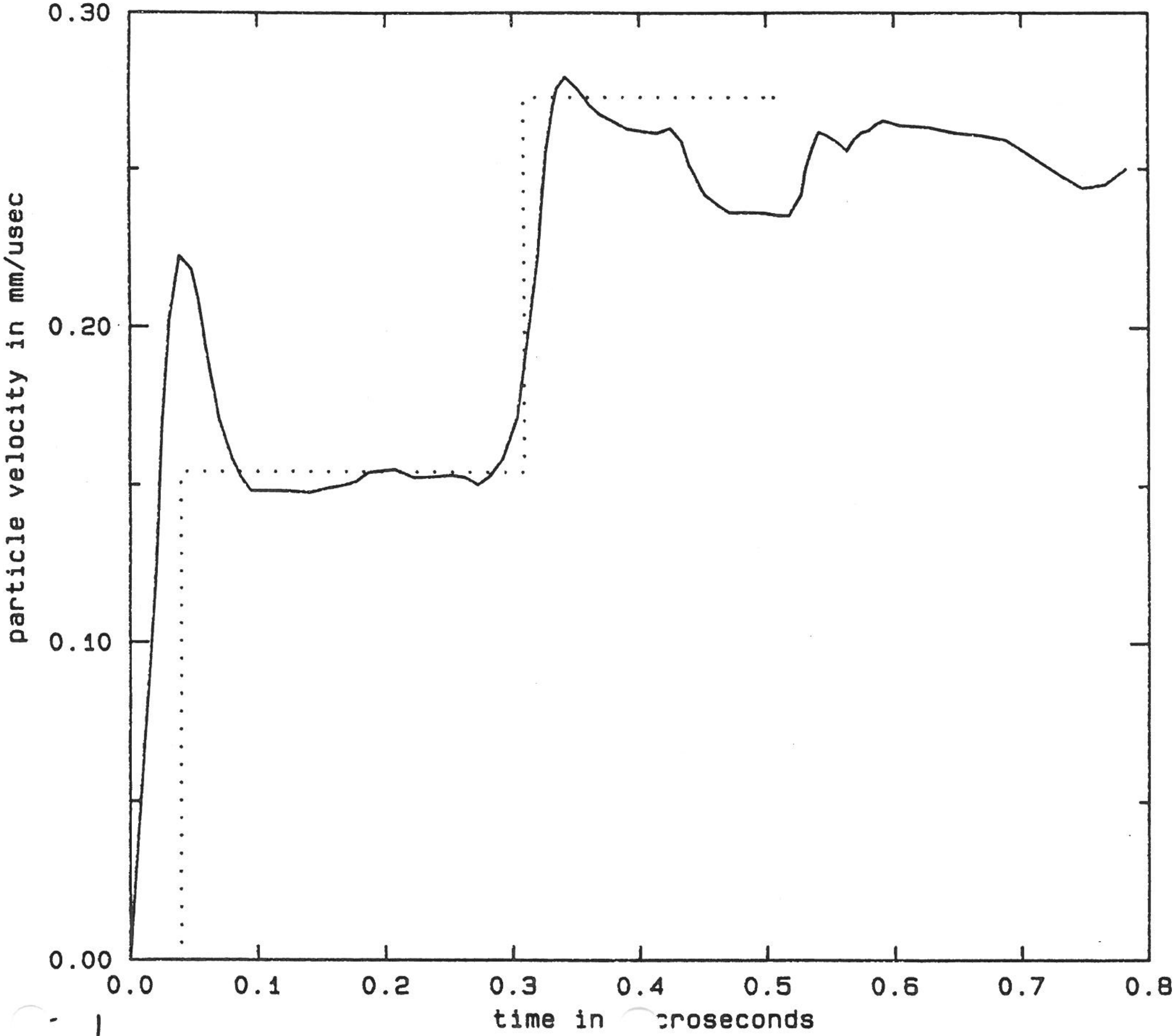


Fig. G.1

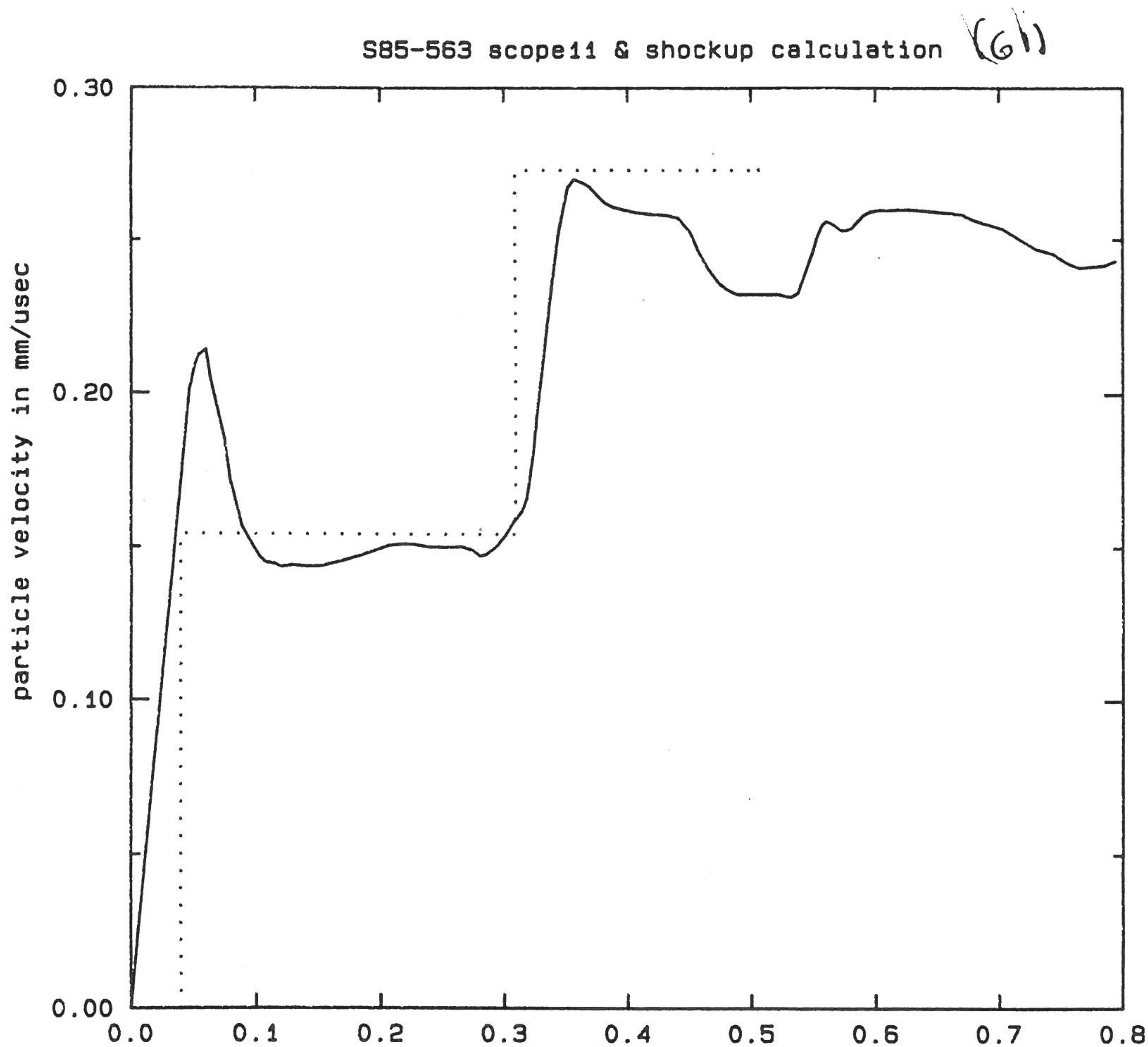

S85-563 scope11 & shockup calculation (G1)
0.30
0.20
0.10
0.00
particle velocity in mm/usec
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Fig. 2

S85-563 scope 16 and shockup calculation (62)

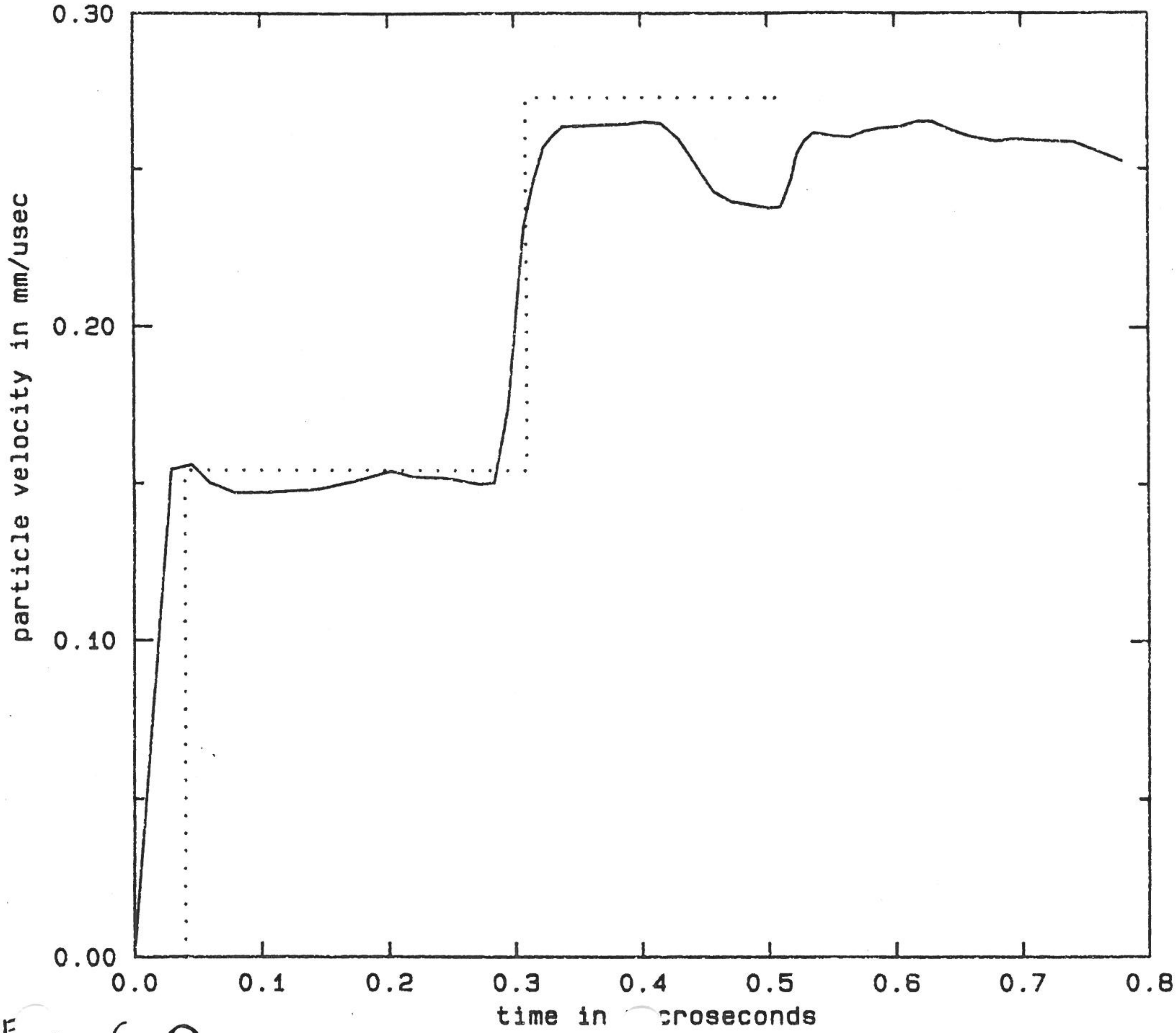


Fig 6.3

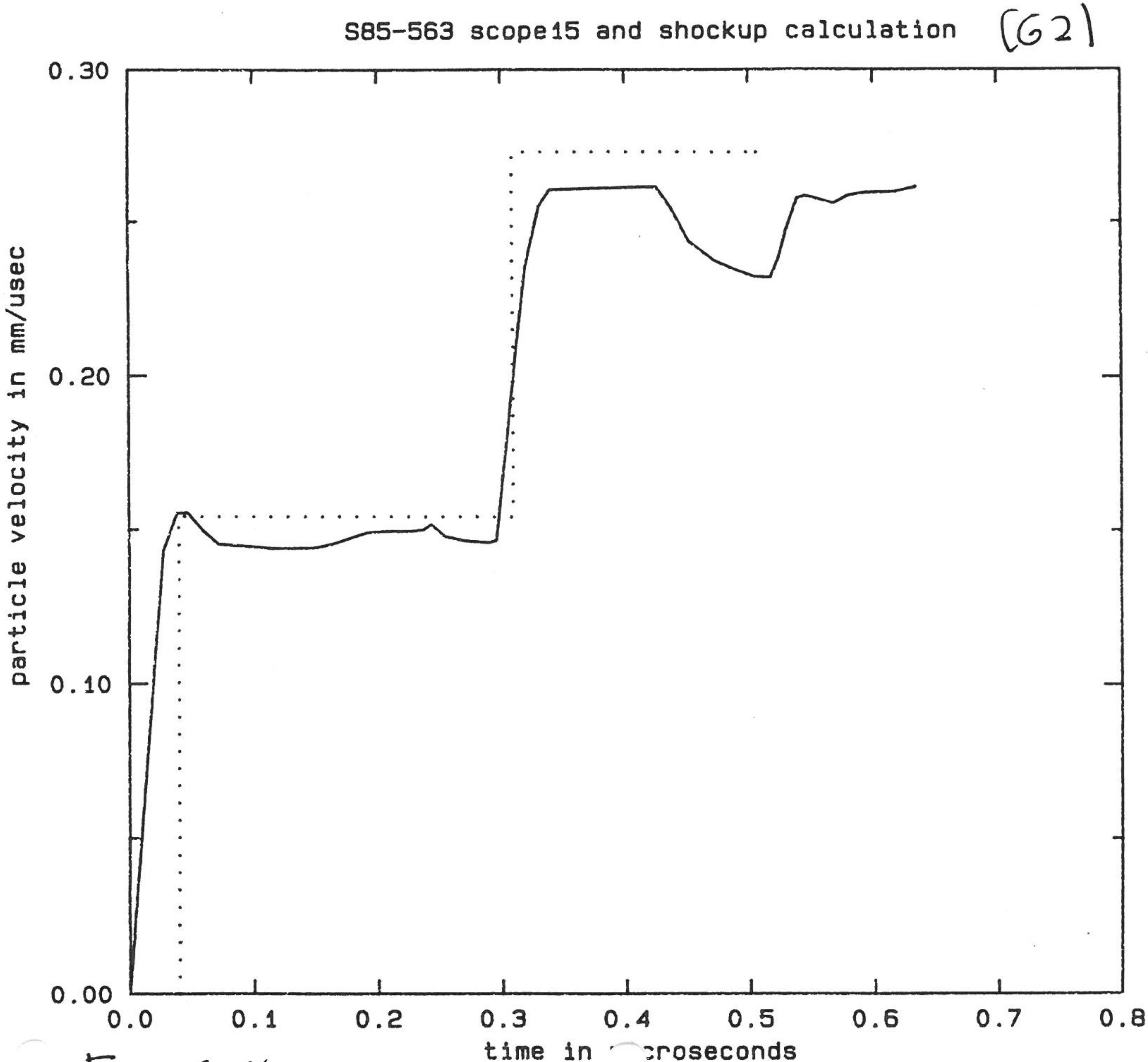
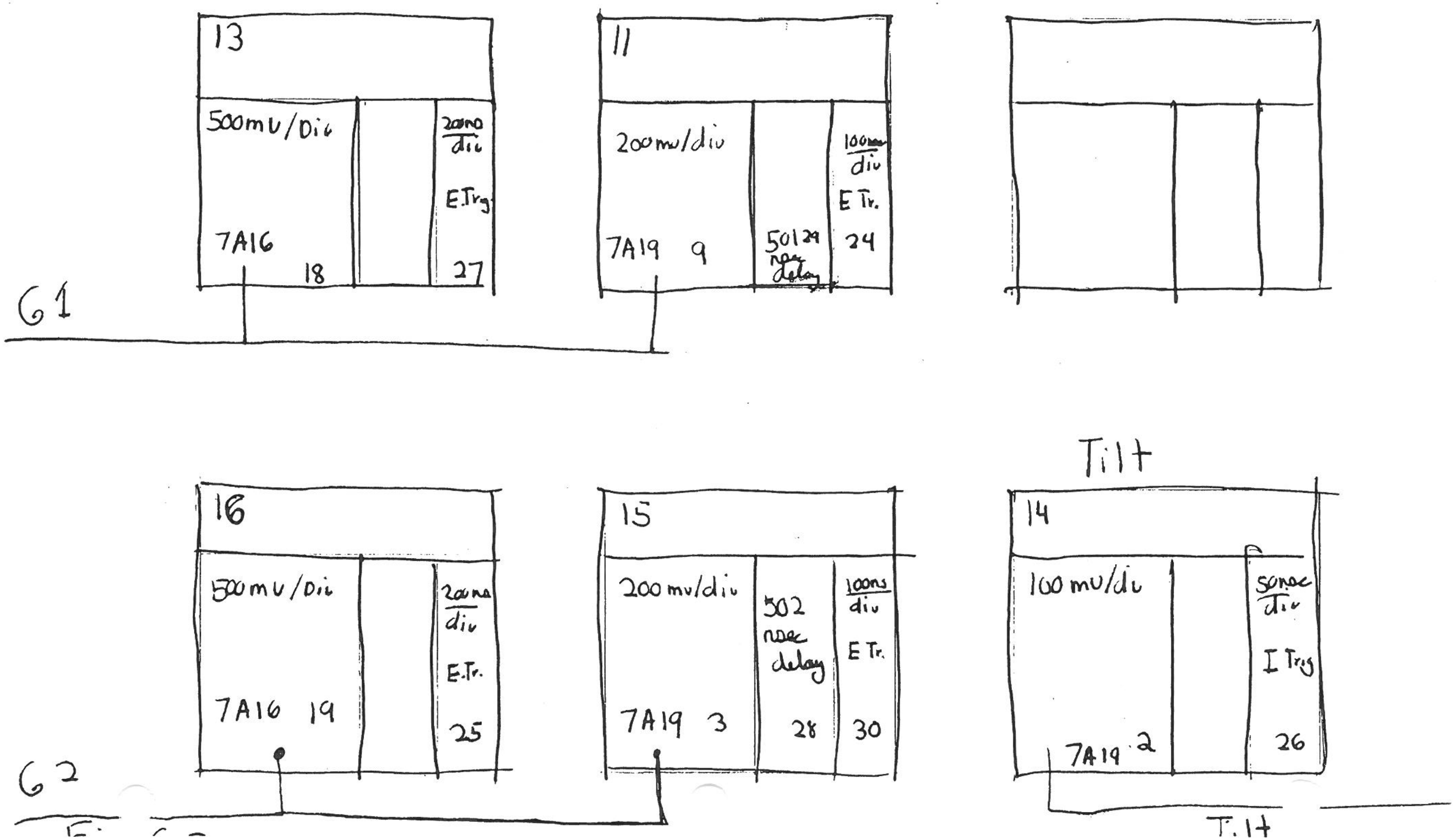

S85-563 scope15 and shockup calculation (G2)
0.30
0.20
0.10
0.00
particle velocity in mm/usec
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
time in croseconds

Fig. 6.4

S 85-563
Scope Setup



Chapter 7

Shot 85-568

Objective

To measure the particle velocity-time profile of a thin layer of CS2 corresponding to a final liquid pressure of 80 kilobar.

Comments

Two gauges were embedded in Vistal. An electroplated gauge (G1) and a foil gauge (G2) of type I configuration were used. Sapphire was chosen for the impactor because a clear window was needed to check if the cell was filled with CS2. Vistal was chosen as a gauge substrate because it is easy to machine and a series of successful have been performed using Vistal [9].

Conclusions

The profile recorded (Figs. 7.1-7.3) with the use of the electroplated gauge was very encouraging. The experimental profile agrees well with the profile calculated by the SHOCKUP program. Minor refinements are needed for this approach to be a successful experimental technique.

The foil gauge measured particle velocities (see Figs 7.2, 7.4 and 7.5) which agreed well with the first particle velocity step of the SHOCKUP calculation. The gauge measured particle velocities which were greater than predicted velocities for the remaining particle velocity steps. This effect may be due to the gauge length not being constant or to a lead effect. Care was taken to make sure the leads were pulled against the edges of the holes (see Fig. 1-4); the leads could not however be visually inspected due to the opaque nature of the Vistal.

b 85-568

ate 10 July85

rojectile vel. - 0.3616 mm/usec

alculated pressure of steps 20.5, 47.1, 65.2, 74.1 and 77.9

ilobars Magnetic Field - 2879 guass

auge 1 length - 10.176 mm (electroplated)

auge 1 resistance - 0.04 ohms

rove depth (G1) - 15-18 um

auge 2 length - 9.636 mm (foil)

auge 2 resistance - 0.11 ohms

roove depth (G2) - 21-28 um

ilt - 2.1 mrad

lyer material - Z-cut sapphire

a et configuration (see Fig. 1) III

arget material (front layer) - Z-cut sapphire

hickness - 3.173 mm

arget material (second layer) - Carbon Disulfide

hickness - 278 microns (measured) 287 microns (shim thick-

ess)

arget material (third layer) - Vistal

hickness - 6.368 mm

omputer file location of records

pper/Srecords/S85-568

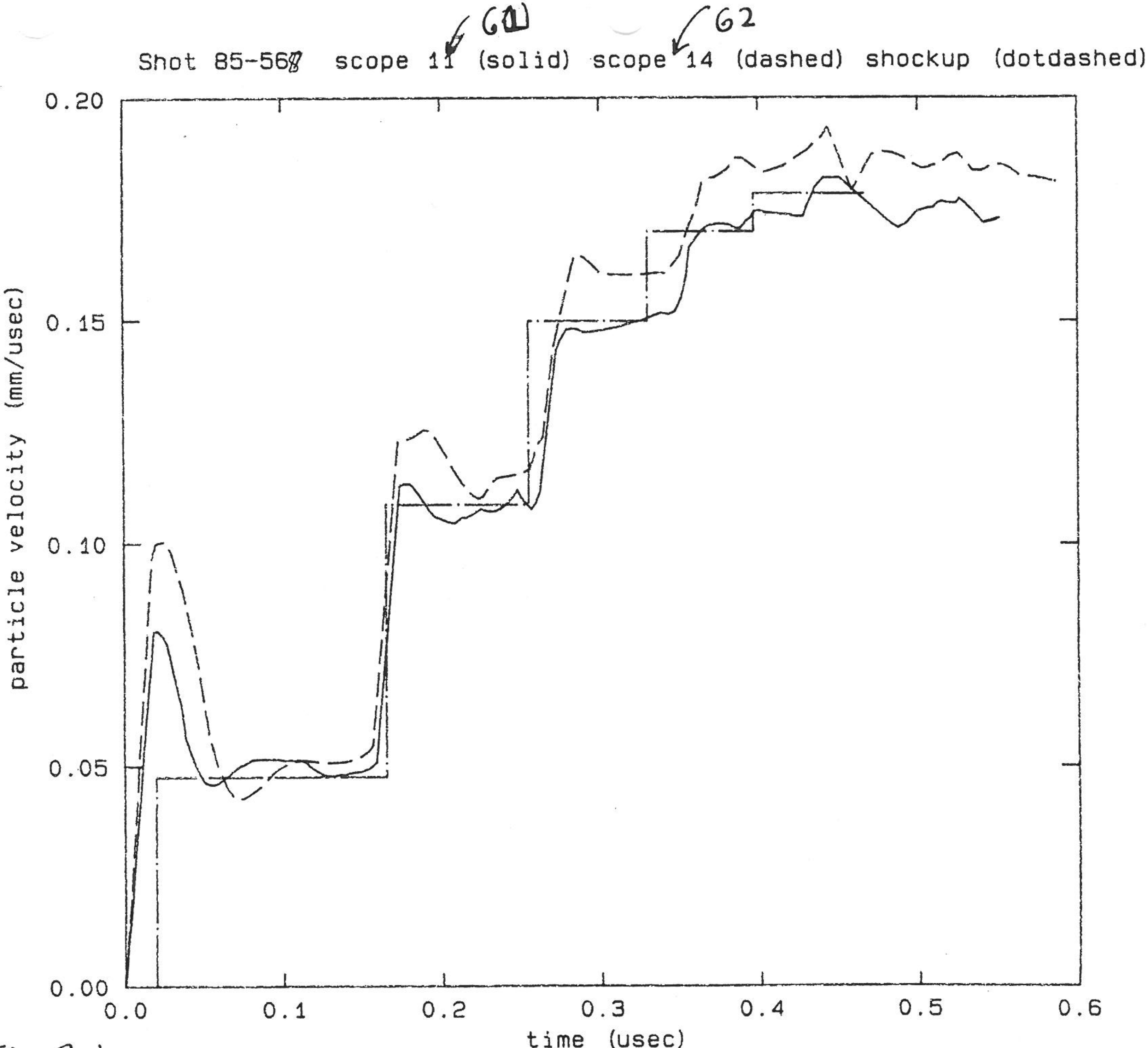

Shot 85-56? scope 11 (solid) scope 14 (dashed) shockup (dotdashed)
0.20
0.15
0.10
0.05
0.00
particle velocity (mm/usec)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
time (usec)

Fig 7.1

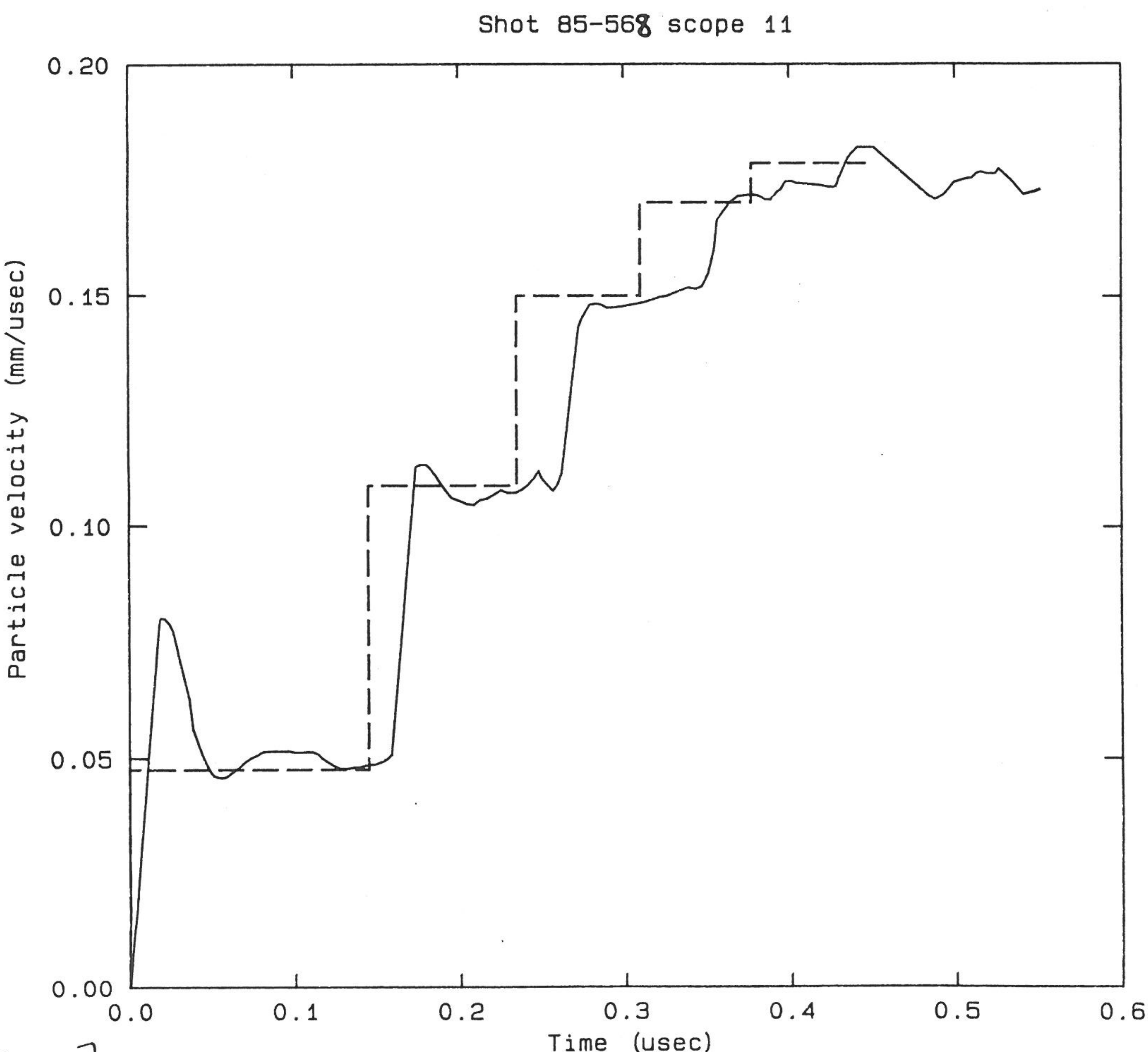

Shot 85-568 scope 11
Particle velocity (mm/usec)
0.00
0.05
0.10
0.15
0.20
Time (usec)
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Fig. 7.2

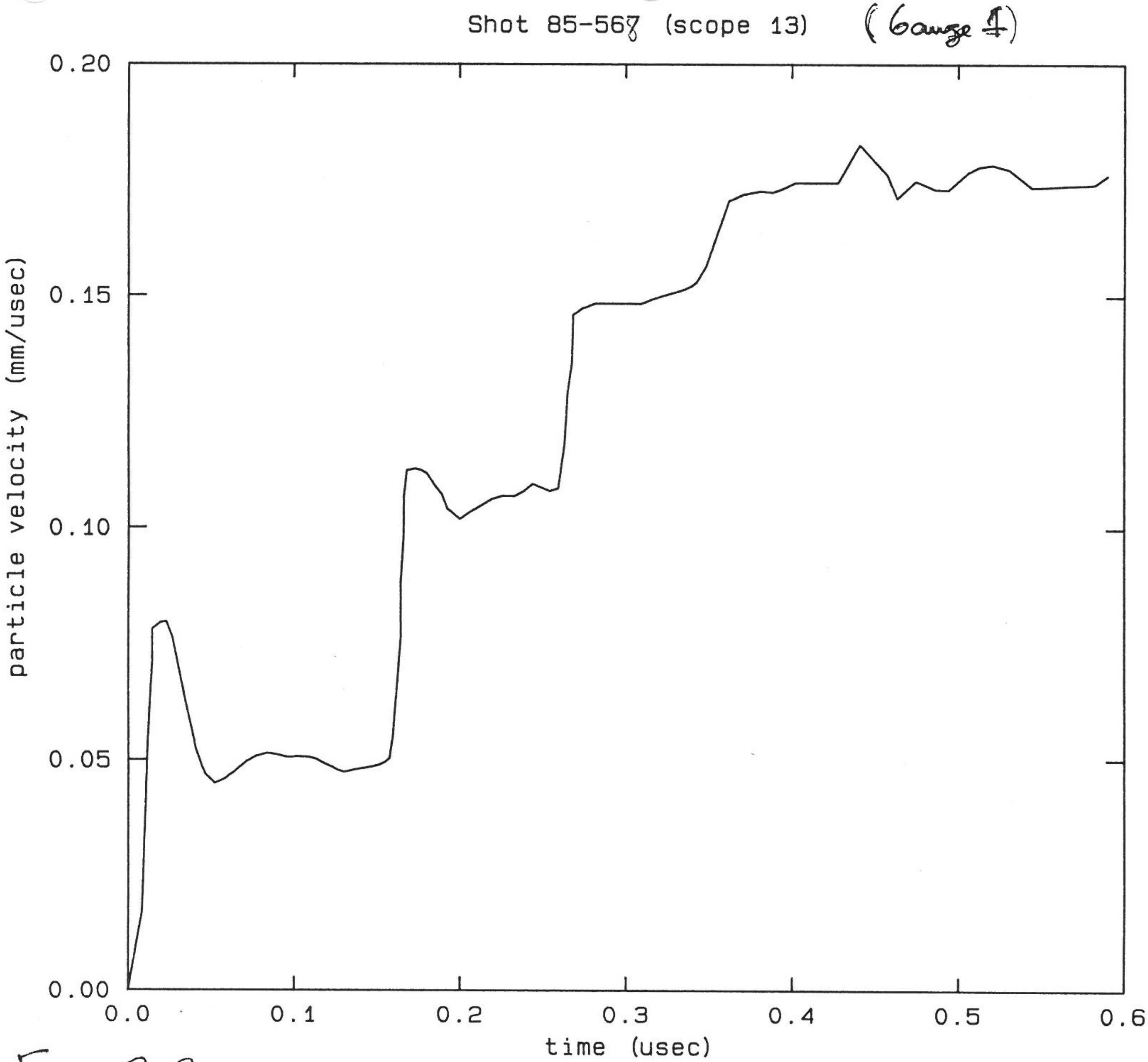

Shot 85-568 (scope 13) (Gauge 4)
0.20
0.15
0.10
0.05
0.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
particle velocity (mm/usec)
time (usec)

Fig. 7-3

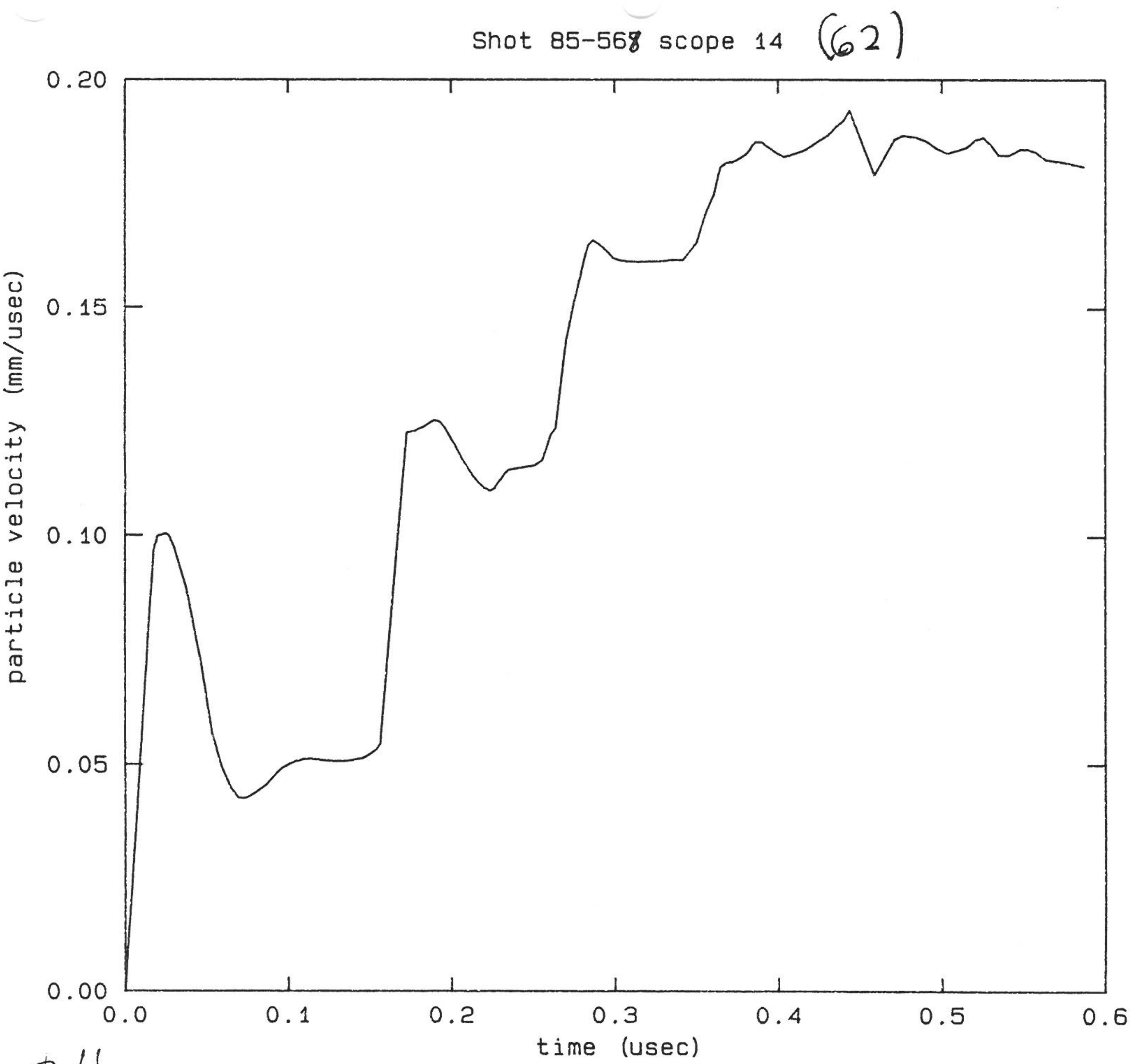

Shot 85-567 scope 14 (62)
0.20
0.15
0.10
0.05
0.00
particle velocity (mm/usec)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
time (usec)

Fig D.4

Shot 85-567 (scope 16) (Gauge 2)

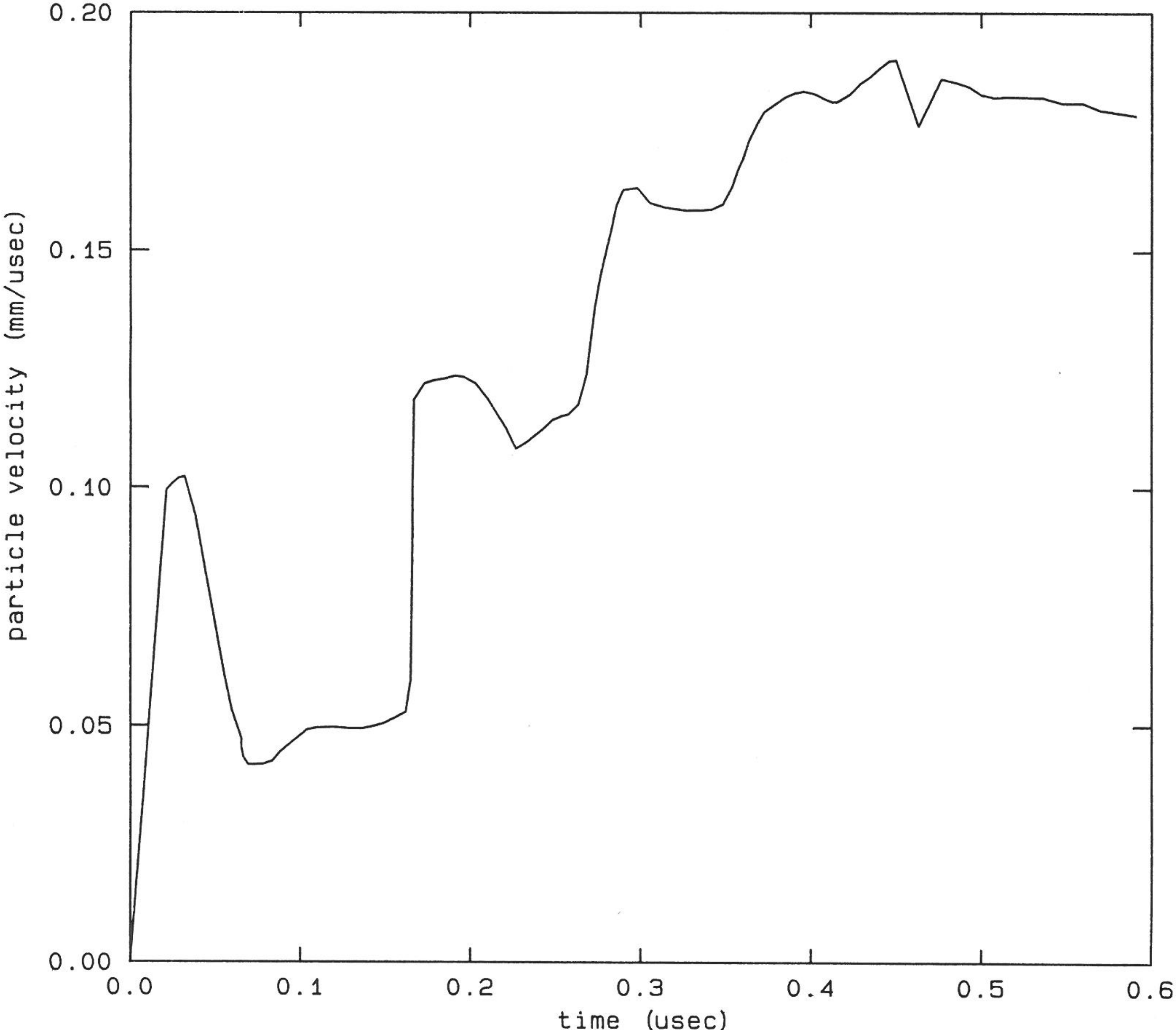


Fig 7.3

S 85-L68
Scope Setup

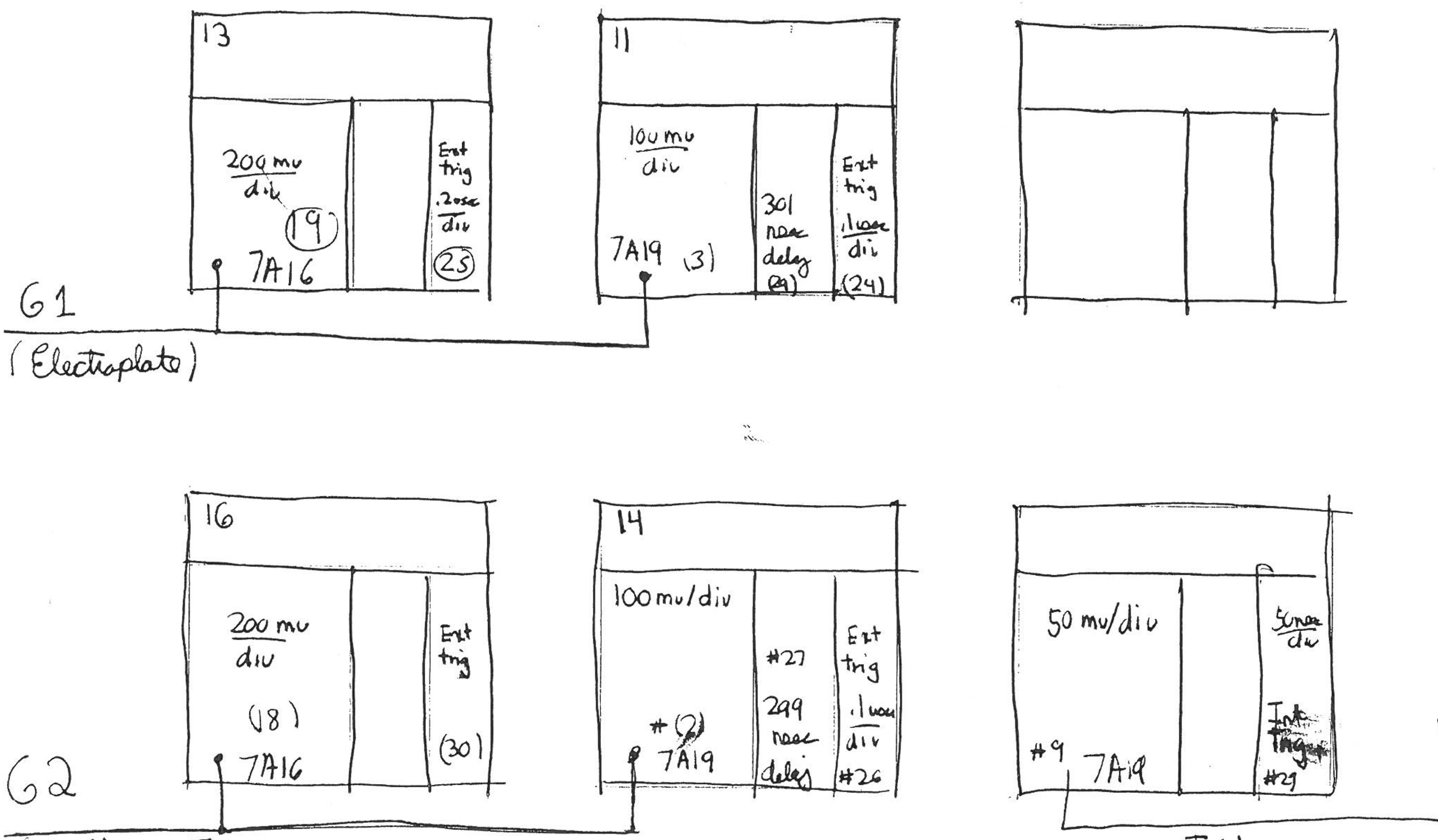


Fig 7.6

Chapter 8

Conclusions and Suggestions

1. The particle velocity-time profile of a liquid can be measured for final liquid pressures to 80 kilobar, with some refinement, with electroplated gauges.

2. Foil gauges perform well when placed in a fused silica matrix.

3. Great care should be exercised when making any type of particle velocity gauge.

4. The experimental technique described here should be perfected using a Vistal [3] cell back before using a Z-cut sapphire

5. An amalgam gauge would be worth testing.

References

1. G.T. Sutherland, M.S. thesis, Pressure Profile of Multiply Shocked Carbon Disulfide, Washington State University, 1984.

2. G.T. Sutherland, Y.M. Gupta, and P.M. Bellamy, J. Appl. Phys, (to be published).

3. Vistal is a trade of COORS Porcelain for polycrystalline alumina. It is slightly larger than 2.25 inches in diameter.

4. The gauges were sanded until they were about 0.0001 inches above the substrate.

5. P.P. Majewski, Ph.D. thesis, Particle Velocity Measurements In Shocked Lithium Fluoride, Washington State University, 1983.

6. Kendal M. Ogilivie, George E. Duvall, and Robin Collins, computer program SHOCKUP(Washington State University, 1984. (unpublished)

7. L.M. Barker and R.E. Hollenbach, J. Appl. Phys. 41, 4208 (1970).

8. S.A. Sheffield and G.E. Duvall, J. Chem Phys. 78, 1077 (1983).

9. Y.M. Gupta, J. Geophys. Res. 88, 4304 (1983).