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FINAL REPORT

submitted to

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Space Science Branch
ATTN: Eric L. Christiansen
Houston, TX 77058

for research entitled

HYPERVELOCITY IMPACT SIMULATION FOR MICROMETEORITE AND DEBRIS SHIELD DESIGN

Submitted by

Eric P. Fahrenthold
Department of Mechanical Engineering
University of Texas
Austin, TX 78712

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ABSTRACT

A new capability has been developed for direct computer simulation of hypervelocity impacts on multi-plate orbital debris shields, for combinations of low shield thickness and wide shield spacing which place extreme demands on conventional Eulerian analysis techniques. The modeling methodology represents a novel approach to debris cloud dynamics simulation, a problem of long term interest in the design of space structures. Software implementation of the modeling methodology provides a new design tool for engineering analysis of proposed orbital debris protection systems.

ACKNOWLEDGEMENTS

This work was funded under the NASA Regional Universities Grant Program. The assistance of Eric L. Christiansen (NASA Technical Officer) and Jeanne Lee Crews of the Space Science Branch of Johnson Space Center has been greatly appreciated. Additional support was provided by Cray Research, Inc. under the Cray University Research and Development Grant Program and by the Texas Higher Education Coordinating Board under the Energy Research in Applications Program. Computer time was provided by the Center for High Performance Computing and the Institute for Advanced Technology at the University of Texas at Austin.

SOFTWARE COPYRIGHT NOTICE

Source code developed under this research project has been provided to NASA. Other interested parties should note that this software has been copyrighted (1991) by the principal investigator, as follows:

(1) Software written to link the codes CTH and DYNA2D has been copyrighted as an original work under the title DCT2D (Debris Cloud Translator 2-Dimensional).

(2) Software written to augment the standard DYNA2D code has been copyrighted as a derivative work under the title DCA2D (Debris Cloud Augmentation 2-Dimensional).

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Introduction

This report describes the results of code development work and supercomputer based hydrocode simulations conducted to pursue computer aided design of space debris shielding (Cour-Palais and Crews, 1990 and Christiansen, 1990).

Previous progress reports (Fahrenthold, 1990a and b, and 1991a) have discussed a number of hypervelocity impact simulations conducted using the Sandia National Laboratories hydrocodes CSQ (Thompson, 1990a) and CTH (McGlaun et al., 1990), to evaluate their utility in modeling impacts on multi-plate debris shields. The results of that work suggested that existing Eulerian codes are not well suited for use in direct computer simulation of impacts on multi-plate debris shields. Recognizing the limitations of available Eulerian codes, the last progress report (Fahrenthold, 1991b) described an alternative approach to simulation of the problem of interest. This approach combined Eulerian (CTH) modeling of the shield perforation process with a new Lagrangian model of debris cloud evolution. The Lagrangian debris cloud model was developed using an augmented version of the finite element code DYNA2D (Hallquist, 1987). The basic DYNA2D code was developed at Lawrence Livermore National Laboratories. The DYNA2D augmentation, developed and coded by the principal investigator for use in the present research project, took the form of a mixture theory based (Drumheller, 1987, and Drumheller and Bedford, 1980) equation of state for a solid material containing voids. Additional pre-processing, post-processing, and rezoning routines used to systematically link the CTH and DYNA2D simulations were also developed and coded by the principal investigator. The result is a new computer simulation capability for multi-plate debris shield impacts.

The present report outlines the analysis procedure and describes an example multi-plate debris shield impact simulation. Tables and figures are included after the main body of the report, while the computer graphics depicting the impact simulations are provided as appendices. Suggestions for future work are discussed in the conclusions section.

Analysis procedure

The analysis procedure is represented by the flow charts shown in Figures 1 and 2. As presently formulated, the procedure models two-dimensional (axisymmetric) impact of like materials. Mass, kinetic energy, void volume, and density are conserved in Eulerian-to-Lagrangian or Lagrangian-to-Eulerian translations of debris cloud data. Thermal energy is discarded. Generalization of this analysis procedure is possible, given additional development work. Simulation of the normal impact of a hypervelocity projectile on a multi-plate debris shield proceeds as follows:

(1) Impact of the projectile on the front shield plate is modeled using the Eulerian code CTH (Figure 1). Geometry, material properties, initial velocities, and other input data are specified in the input file *dccth*. The output file (*rscth*) from the CTH simulation is then input to the post-processor CTHED. Using this post-processor, the user selects the region of space containing the debris which must be propagated to the next shield. The mass, velocity, and pressure distribution in the debris cloud is contained in the post-processor output file *dcout*.

(2) Next (Figure 1) the routines *dclink.f* and *dcg2d.f* are used to generate a Lagrangian model of the debris cloud (*dcdyna*), given the Eulerian simulation results (*dcout*) and the geometry, material, and control data contained in the user input files *dcg2d.inp* and *dcbase*.

(3) The file *dcdyna* is input to an augmented version of the Lagrangian code DYNA2D (Figure 2), which incorporates a mixture equation of state for a continuum with voids, as well as a void space evolution equation. The auxiliary input file *rvl2d.dat* created by *dcg2d.f* is required to properly initialize the DYNA2D calculation. A Lagrangian simulation is then used to propagate the debris to the next shield. An auxiliary output file *dcrez.dat* is created for use in initializing the next Eulerian shield impact calculation.

(4) Finally the results of the Lagrangian simulation (*dcrez.dat*) are input to the routine *dcrez.f* (Figure 2), to develop an Eulerian description of the debris cloud impacting

the next shield. The routine *dcrez.f* also requires as input certain geometry, mesh connectivity, and mass distribution data contained in the files *dcrez.inp*, *rvl2d.dat*, and *dcg2d.out*, the latter two having been previously generated by *dcg2d.f*. The output from *dcrez.f*, contained in the file *dcrez.out*, is combined directly with user-specified geometry, material, and control data (*dccth.1* and *dccth.2*) describing the next shield (or wall) impact calculation to be performed. The resulting CTH input file (*dccth*) is used to initiate a repeat cycle of calculations, starting at the aforementioned step (1).

(5) In some cases, one or more rezones of the Lagrangian mesh may be required to propagate the debris between two adjacent shields. In this case (Figure 2), the file *dccth* is created as in step (4), but without a new shield model, and then input to the CTH pre-processor CTHGEN. The resulting output file (*rscth*) is then post-processed using CTHED and a rezoned Lagrangian model is created as in step (2). This Lagrangian rezone procedure is well suited to mixture theory based debris models, although a special (direct) rezone routine could be written for this purpose. Note that the standard DYNA2D rezoner cannot be used in this case, due to the presence of void space in the Lagrangian finite elements. In any case, conventional Lagrangian rezone procedures are ill-suited to this application, due to the extremely complex geometry of the debris clouds.

Although the outlined analysis procedure appears complex, it should be emphasized that the Eulerian-to-Lagrangian and Lagrangian-to-Eulerian translations have been highly automated by the routines *dclink.f*, *dcg2d.f*, and *dcrez.f*. Only two very short input files (*dcg2d.inp* and *dcrez.inp*) beyond those normally required in performing CTH and DYNA2D calculations have been added to the user's data preparation workload, since the remaining auxiliary input files are created automatically by the interface routines. Despite this fact, multi-plate impact simulations are generally user and CPU time intensive, as demonstrated by the series of simulations discussed in the next section.

To illustrate the analysis procedure, consider the representative problem of a 0.32 cm diameter aluminum sphere impacting upon a 0.081 cm thick aluminum plate at a velocity of 6.58 km/sec (Cour-Palais and Crews, 1990). Appendix A shows the results of a CTH simulation of such an impact, including: (1) a legend for the mass density plots which follow (page A-2), and (2) four mesh density plots describing the first one and one-half microseconds after impact, spaced at intervals of one-half microsecond (pages A-3 through A-6). At one and one-half microseconds the CTH simulation was terminated and a Lagrangian (DYNA2D) model of the debris cloud was generated using the Eulerian-to-Lagrangian model translation routines just discussed. Comparison of the Lagrangian debris cloud model (page A-7) with the debris cloud state at the end of the Eulerian simulation (page A-6) illustrates the accuracy of the model translation procedure, although the presence of variable amounts of void space in the finite elements shown on page A-7 must be kept in mind. Mass and kinetic energy error associated with the model translation process is typically less than one percent. Given an initial density, velocity, and void volume distribution obtained from the CTH simulation, the Lagrangian (DYNA2D) model is then integrated to propagate the debris. At two and one-half microseconds after impact, one microsecond after ending the Eulerian simulation, the debris cloud has evolved to the form shown on page A-8. Note that the radius of the debris cloud has increased significantly, and that the leading edge of the debris cloud has translated along the impact centerline. The shell of the debris has thinned as it expands, while the spreading of debris particles within the shell illustrates the presence of velocity variations across the debris cloud. The analysis reflects (qualitatively) observed behavior in impact experiments, and avoids previously reported problems (Fahrenthold, 1990a and b, and 1991a) associated with debris propagation by Eulerian simulations.

Effective use of the simulation approach just discussed in debris shield design applications depends upon experimental validation of the models employed. The next section describes a series of calculations conducted to simulate a multi-plate shield impact experiment performed by Cour-Palais and Crews (1990).

Multi-plate shield impact simulation

This section describes a representative multi-plate shield impact modeling problem, simulated using a coordinated Eulerian-Lagrangian approach. Supporting figures are provided in Appendices B through F, while simulation parameters are listed in Table 1. The problem involves normal impact of a 0.32 cm diameter sphere on a series of four bumper plates of thickness 0.0102 cm followed by a wall of thickness 0.079 cm (Figure 3). The plate-to-plate and plate-to-wall spacing was 2.54 cm. The corresponding experiment is described by Cour-Palais and Crews (1990), as shot #444.

The CTH simulations were performed with a mesh density of at least 62,500 zones per square centimeter. This mesh density exceeds by a factor of 6.25 that used by the CTH code development group in their published study of a canonical debris cloud problem (Trucano and McGlaun, 1990). Transmitting boundary conditions (McGlaun, 1982) were used to accommodate backsplash and debris transport outside the modeled region. The simulations employed the first momentum advection option (CONV=1, Trucano and McGlaun, 1990) in the CTH code. This option conserves momentum in mapping the deformed material mesh to the space-fixed mesh, while discarding any kinetic energy error associated with the remap. This option is recommended by the CTH code development group (Trucano and McGlaun, 1990). The ANEOS (Thompson, 1990b) library equation of state for aluminum, with melting, was employed to model the projectile, shield, and wall materials.

The DYNA2D simulations were performed using models composed of up to 4,015 four-noded quadrilateral elements. The debris cloud was modeled as an isotropic, elastic-plastic hydrodynamic material (aluminum) with voids, and the following material properties (g-cm-µsec system of units): shear modulus = 0.250 g/(cm-µsec^2), bulk modulus = 6.52 x 10^{-1}g/(cm-µsec^2), plastic hardening modulus = 6.67 x 10^{-2}g/(cm-µsec^2), and yield strength = 3.45 x 10^{-3}g/(cm-µsec^2). The void volume evolution equation used here took the form

$$\dot{\phi} = -[\alpha/(\gamma_o/\rho)^2] \min\{ 0.0, P/[(1-\phi)\rho] \} \; ; \; \alpha = 0.10 \mu sec/cm^2$$

where ϕ is the void volume, γ_o is the true reference density, ρ is the bulk density, and P is the bulk pressure (Fahrenthold, 1991b).

The following paragraphs briefly describe the series of fourteen Eulerian and Lagrangian simulations required to model the perforation of all four shields and impact on the wall plate. The simulations are referred to by the codes listed in the first column of Table 1. The analysis was performed on a state-of-the art supercomputer, namely a Cray Y-MP/864 located at the University of Texas System Center for High Performance Computing. The maximum memory requirement was eight megawords. The total required CPU time was 9.68 hours, for a simulation time of 20.11 microseconds.

The first CTH simulation ("nasa1a" in Table 1) modeled perforation of the the first shield plate. Appendix B shows four mass density plots (pages B-3 through B-6) describing the first one and one-half microseconds after impact, spaced at intervals of one-half microsecond. The calculation required 2,913 CPU seconds. At one and one-half microseconds the CTH simulation was terminated and a DYNA2D model of the debris cloud was generated (page B-7). This model ("dcex1a" in Table 1) was used to simulate motion of the debris cloud towards the second plate, requiring 9,955 CPU seconds for a simulation time of two microseconds. The state of the debris cloud at 3.5 microseconds after impact, i.e. at the end of this Lagrangian simulation, is shown on page B-8. At this point the results of the Lagrangian calculation were used to generate a new Eulerian model for impact simulation on the second plate.

The results of the second CTH simulation (nasa1b) are shown in Appendix C, which includes nine mass density plots spaced at intervals of 0.2 microseconds (pages C-3 through C-11). Comparison of the debris cloud models at the end of the first Lagrangian simulation (page B-8) and the start of the second Eulerian simulation (page C-3) illustrates the model translation process. Note that in the interest of reducing CPU time requirements, some of the widely dispersed debris present at the end of the first DYNA2D simulation (page B-8) is neglected in the Lagrangian-to-Eulerian remap. The CTH model of the second shield impact required 5,274 CPU seconds for a simulation time of 1.6 microseconds, ending at 5.1 microseconds after initial impact on the first plate. At this point a DYNA2D model (dcex1b) of the debris cloud in the region 0.0 < x < 0.4, -7.50 < y < -6.76 shown on page C-11 was formulated, as indicated in the sixth and seventh columns of Table 1. (Note that "x" and "y" are radial and axial coordinates for these axisymmetric problems.) This DYNA2D model incorporated 4,015 elements (see column eight in Table 1). To reduce the excessive CPU time requirements associated with such a large number of elements, this model was rezoned (to model "dcex1ba" in Table 1) before propagating the debris to the third shield with a Lagrangian simulation ending at 7.81 microseconds after initial impact.

The results of third and fourth shield perforation calculations, made using CTH, are shown in Appendices D and E. Appendix D shows nine mass density plots (pages D-3 through D-11) spaced at intervals of 0.2 microseconds, depicting perforation of the third shield during the time period between 7.81 and 9.41 microseconds after initial impact. That calculation (nasa1c) required 2,516 CPU seconds. Appendix E shows nine mass density plots (pages E-3 through E-11) spaced at intervals of 0.2 microseconds, depicting perforation of the fourth shield during the time period between 12.61 and 14.21 microseconds after initial impact. That calculation (nasa1d) required 2,530 CPU seconds. Propagation of the debris between the third and fourth shields (models dcex1c, dcex1ca, and dcex1cb in Table 1) and between the fourth shield and the wall (models dcex1d, dcex1da, and dcex1db in Table 1) involved DYNA2D simulations like those discussed in the last paragraph. In each case two Lagrangian rezones were required to complete the analysis.

Final simulation of debris cloud impact on the wall structure is depicted in Appendix F. That appendix includes eleven mass density plots, spaced at intervals of 0.2

microseconds, depicting impact on the wall plate over the time period between 18.11 and 20.11 microseconds after initial impact. The calculation (nasa1e) required 10,518 CPU seconds. As indicated by the plot on page F-13, the predicted result is a hole of diameter 0.3 cm in the wall plate. This compares favorably with the experimental result of a torn wall plate, with damage dimensions approximately 0.2 cm x 0.5 cm (Cour-Palais and Crews, 1990).

Conclusion

This research effort has developed a capability for direct computer simulation of multi-plate shield impacts, for combinations of low shield thickness and wide shield spacing which place extreme demands on conventional Eulerian analysis techniques. The modeling methodology represents a new approach to debris cloud dynamics simulation, a problem of long term interest in the design of space structures. Software implementation of the modeling methodology provides a new design tool for engineering analysis of proposed orbital debris protection systems.

Future work can profitably focus on two areas:

(1) Additional simulation work is needed, to further critique the modeling methodology used here against a range of hypervelocity impact experiments. Of particular importance is the effect of variations in material properties and constitutive equations on model predictions at various impact velocities.

(2) Additional software development work is needed to provide the capability for three dimensional simulation of oblique impact effects on proposed debris shield designs. Extension of the modeling approach presented here to three dimensions is direct, and well motivated by the extremely large computer time requirements of three dimensional Eulerian hydrocode simulations.

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Table 1. Simulation parameters: multi-plate shield impact

Simulation code	Simulation type E=Eulerian L=Lagrangian	Start time (micro-seconds)	End time (micro-seconds)	CPU time (seconds) Cray Y-MP/864	X range (cm) xmin ; xmax	Y range (cm) ymin ; ymax	Number of Eulerian zones	Number of Lagrangian elements
nasa1a	E	0.00	1.50	2,913	0.00 ; 1.00	9.00 ; 11.00	250 x 500	-
dcex1a	L	1.50	3.50	9,955	0.00 ; 0.40	8.00 ; 8.70	-	2,423
nasa1b	E	3.50	5.10	5,274	0.00 ; 1.00	6.30 ; 8.80	250 x 750	-
dcex1b	L	5.10	5.11	775	0.00 ; 0.40	6.76 ; 7.50	-	4,015
dcex1ba	L	5.11	7.81	95	0.00 ; 0.30	6.80 ; 7.50	-	241
nasa1c	E	7.81	9.41	2,516	0.00 ; 1.00	4.10 ; 6.60	250 x 625	-
dcex1c	L	9.41	9.41	0	0.00 ; 0.30	4.40 ; 5.20	-	3,243
dcex1ca	L	9.41	10.41	114	0.00 ; 0.30	4.40 ; 5.20	-	273
dcex1cb	L	10.41	12.61	44	0.00 ; 0.40	3.90 ; 4.80	-	301
nasa1d	E	12.61	14.21	2,530	0.00 ; 1.00	1.60 ; 4.10	250 x 625	-
dcex1d	L	14.21	14.21	0	0.00 ; 0.25	2.80 ; 2.05	-	2,610
dcex1da	L	14.21	14.71	84	0.00 ; 0.25	2.80 ; 2.05	-	290
dcex1db	L	14.71	18.11	37	0.00 ; 0.30	2.50 ; 1.70	-	353
nasa1e	E	18.11	20.11	10,518	0.00 ; 1.00	1.50 ; -0.50	250 x 750	-

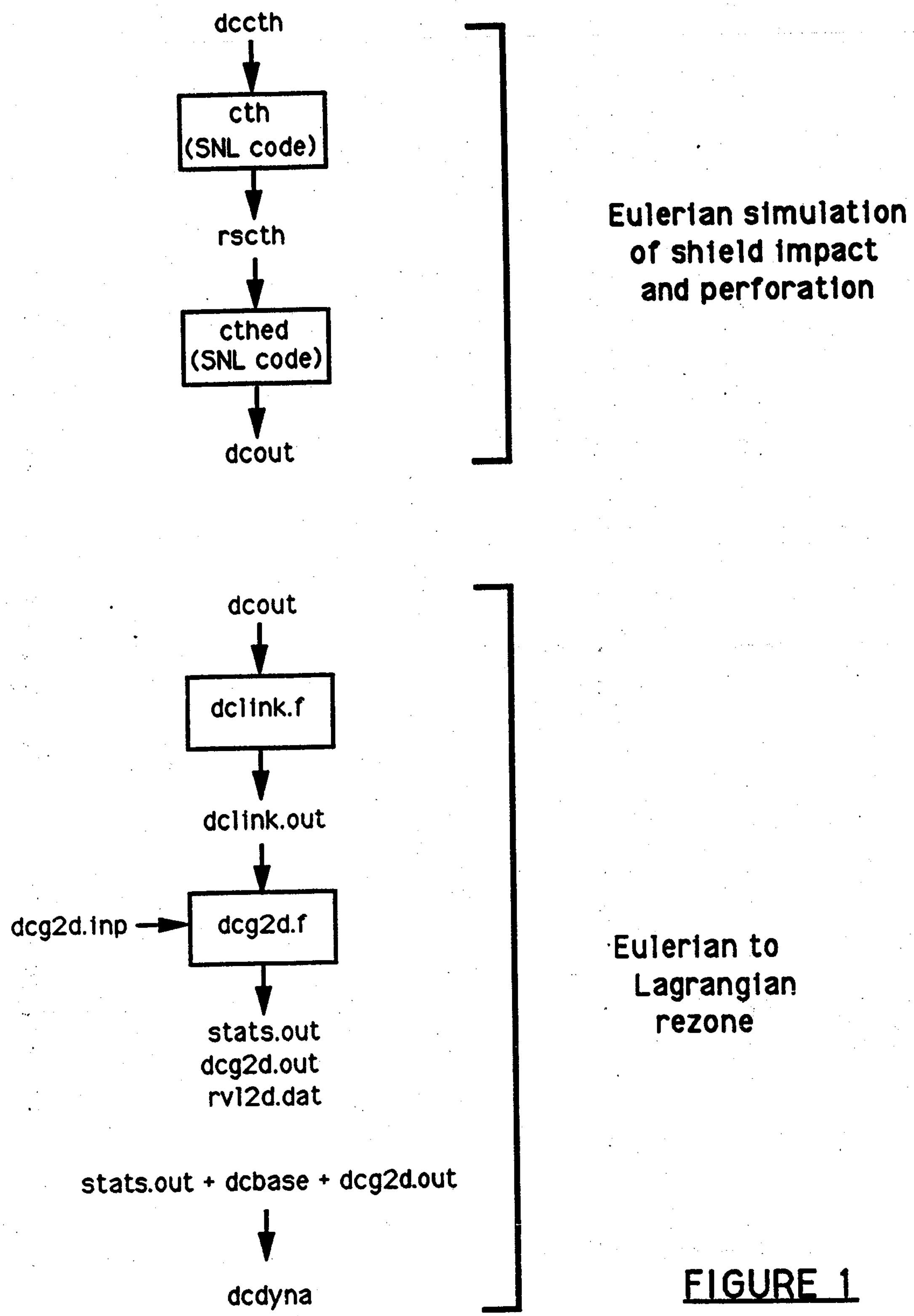
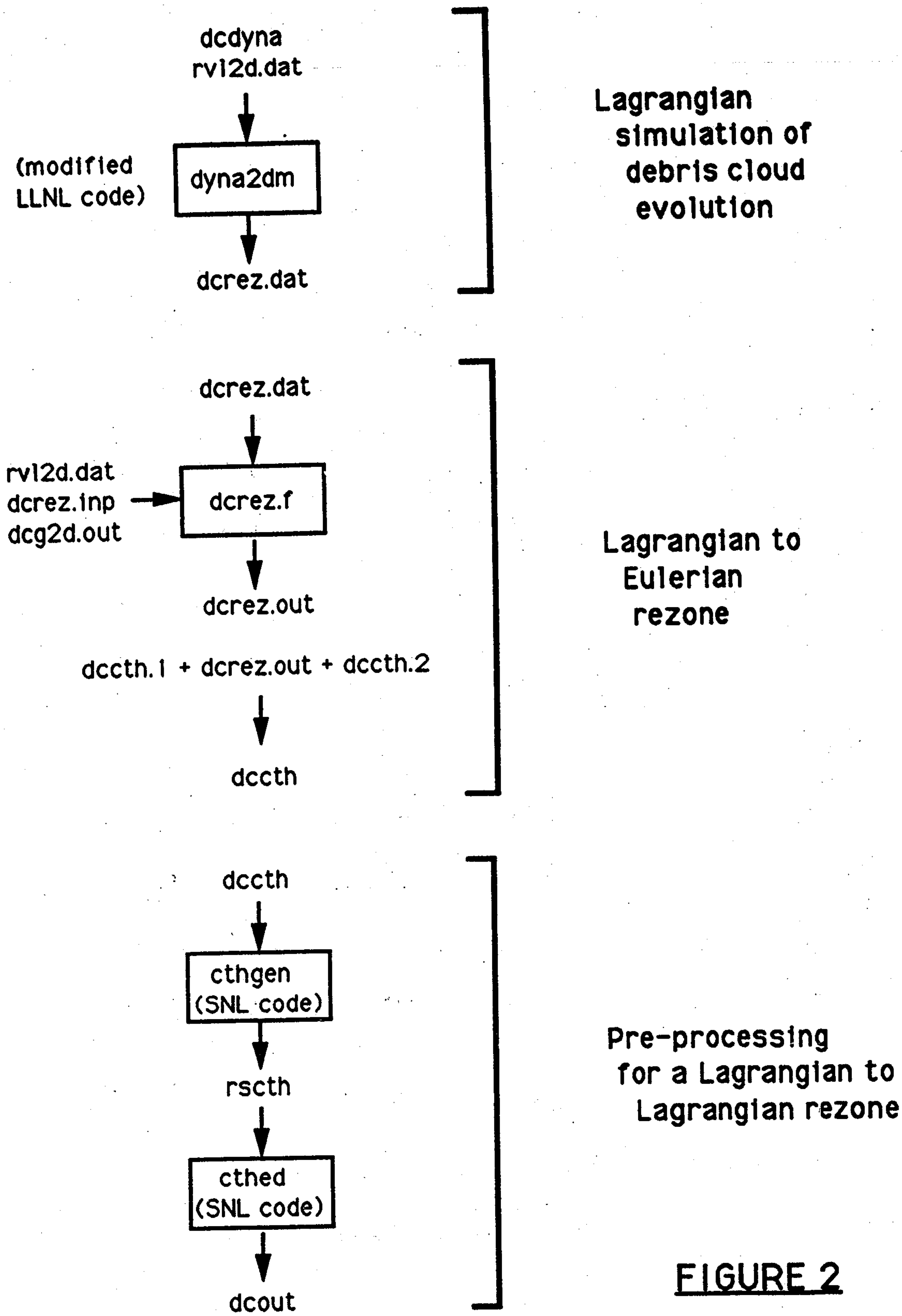

dccth
cth
(SNL code)
rscth
cthed
(SNL code)
dcout
Eulerian simulation
of shield impact
and perforation
dcout
dclink.f
dclink.out
dcg2d.inp
dcg2d.f
stats.out
dcg2d.out
rvl2d.dat
stats.out + dcbase + dcg2d.out
dcdyna
Eulerian to
Lagrangian
rezone

FIGURE 1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rvl2d.dat
(modified
LLNL code)
dyna2dm
dcrez.dat
Lagrangian
simulation of
debris cloud
evolution
dcrez.dat
rvl2d.dat
dcrez.inp
dcg2d.out
dcrez.f
dcrez.out
dccth.1 + dcrez.out + dccth.2
dccth
Lagrangian to
Eulerian
rezone
dccth
cthgen
(SNL code)
rscth
cthed
(SNL code)
dcout
Pre-processing
for a Lagrangian to
Lagrangian rezone

FIGURE 2

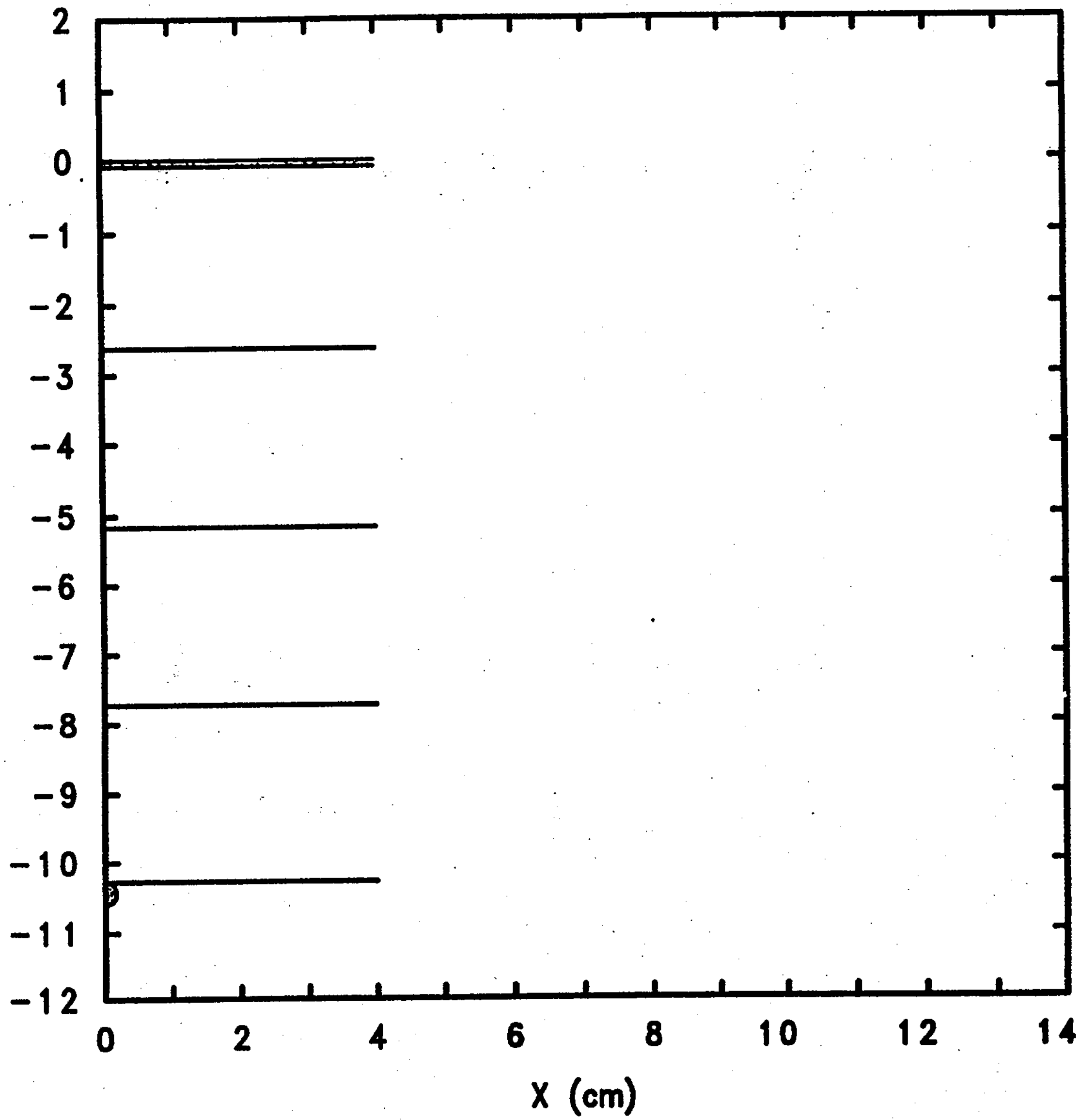


Figure 3. Multi-plate shield impact problem

APPENDIX A

Legend

Density (g/cm^3)

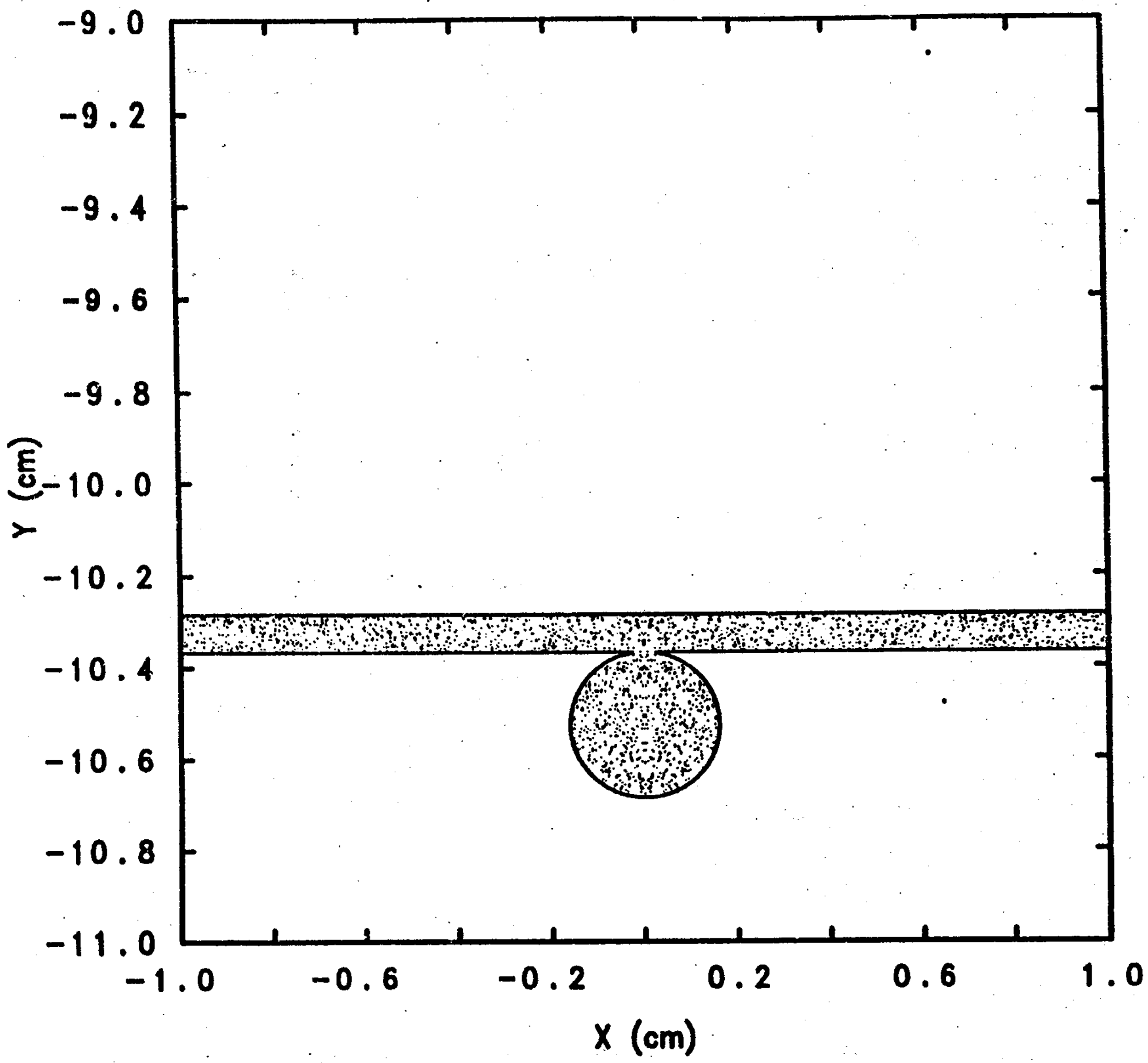
7.500E-01

1.500E+00

3.000E+00

6.000E+00

1.200E+01



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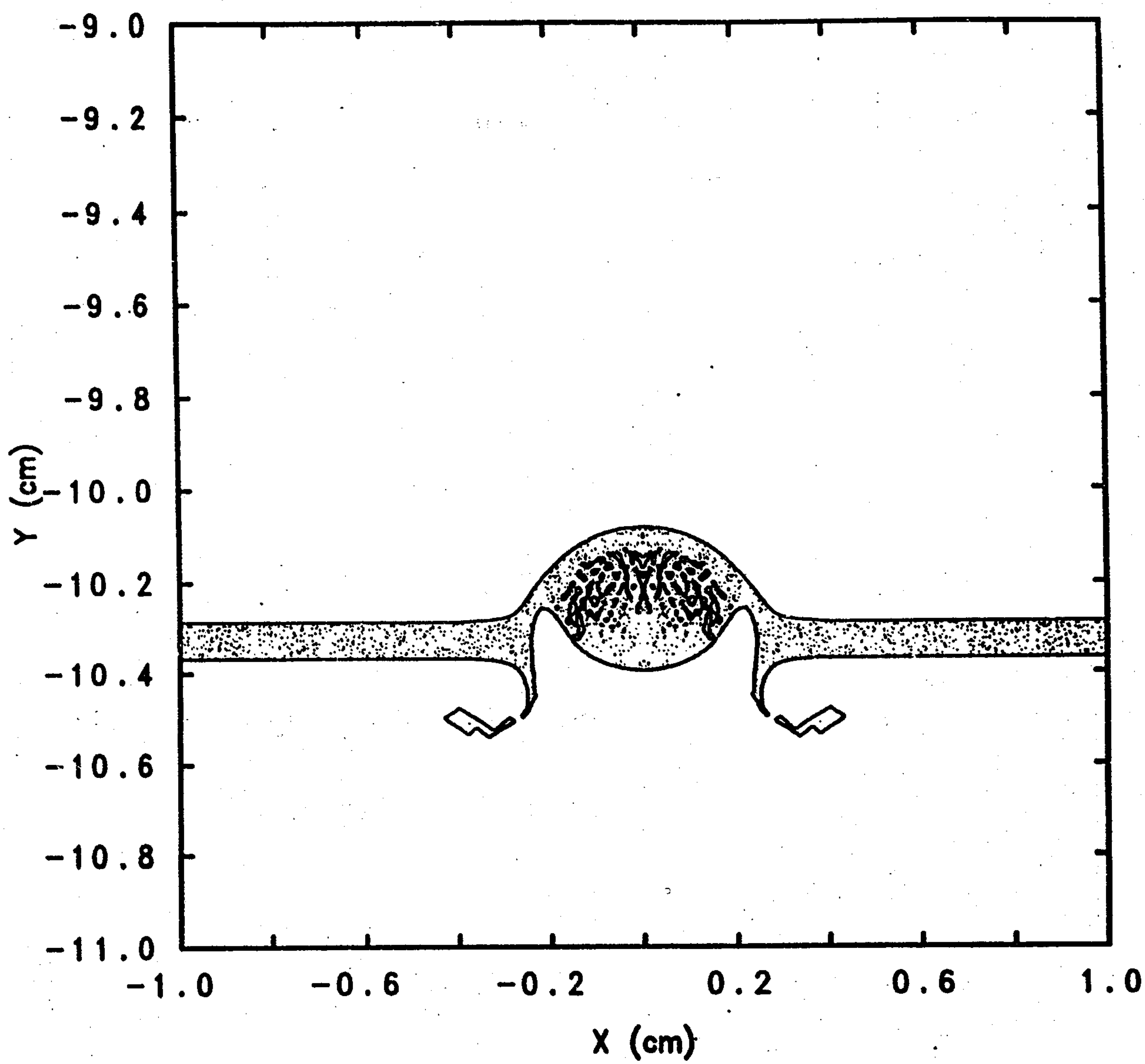

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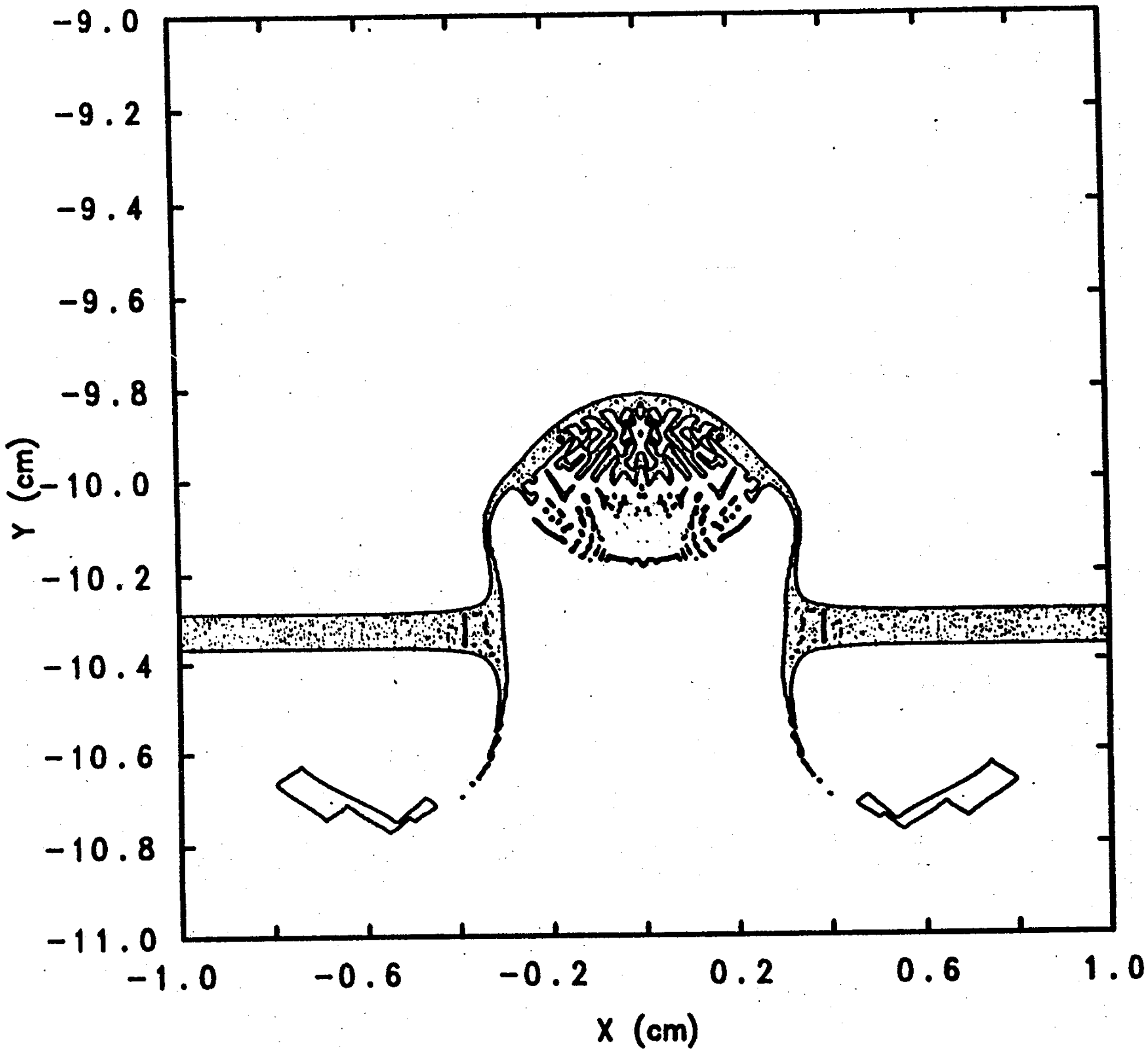
A-4



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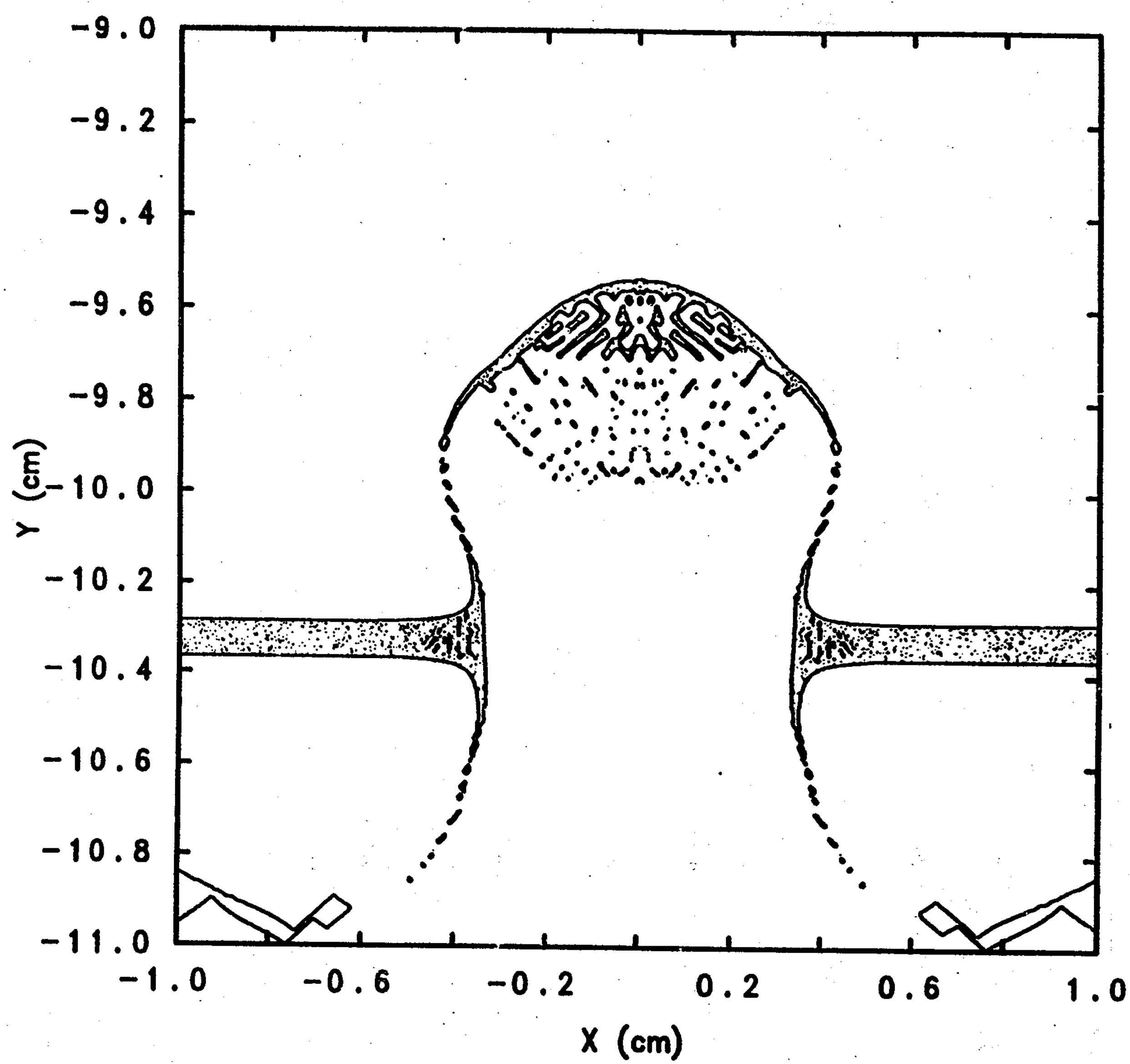

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DYNA2D Debris Cloud Model
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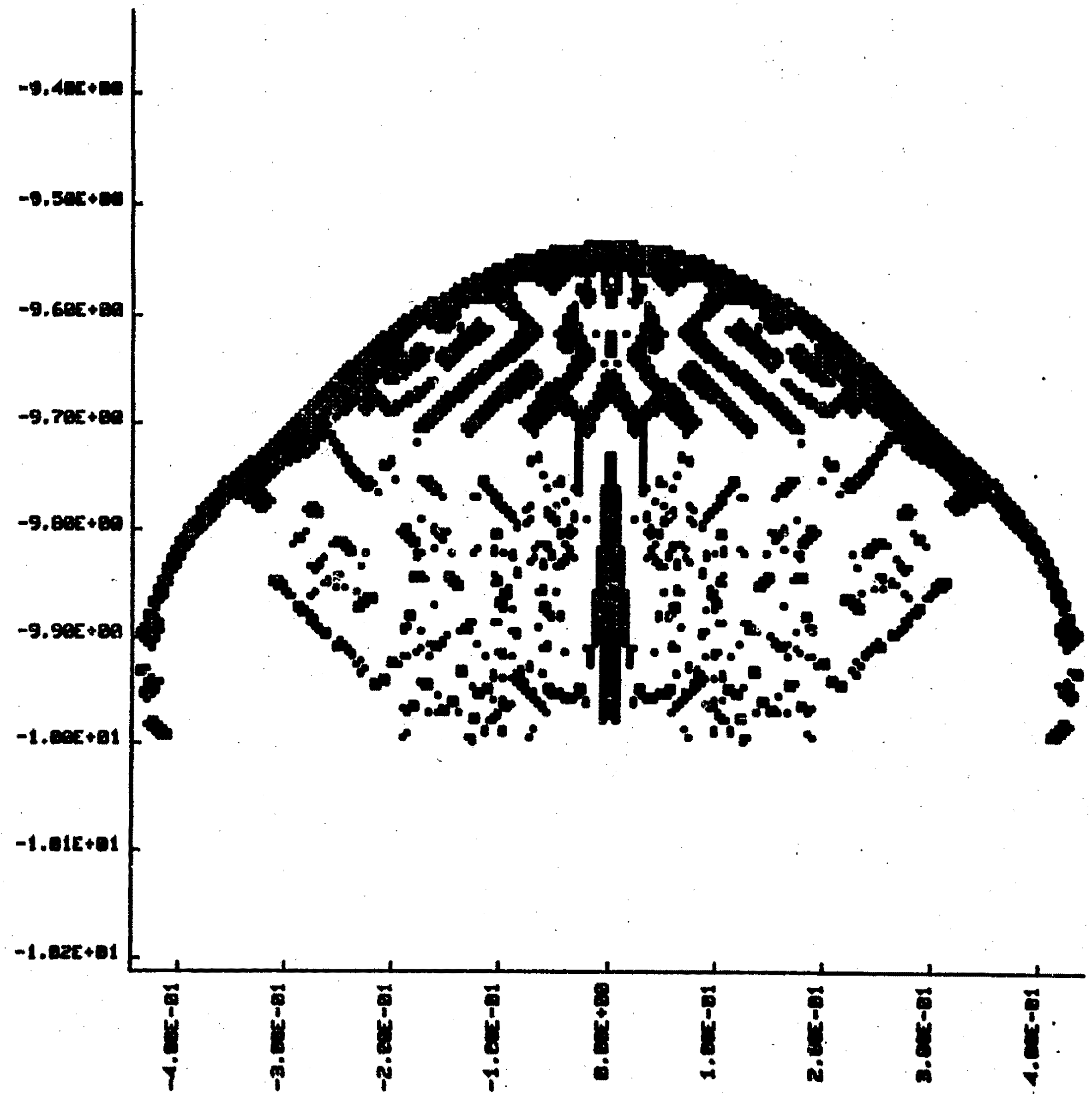

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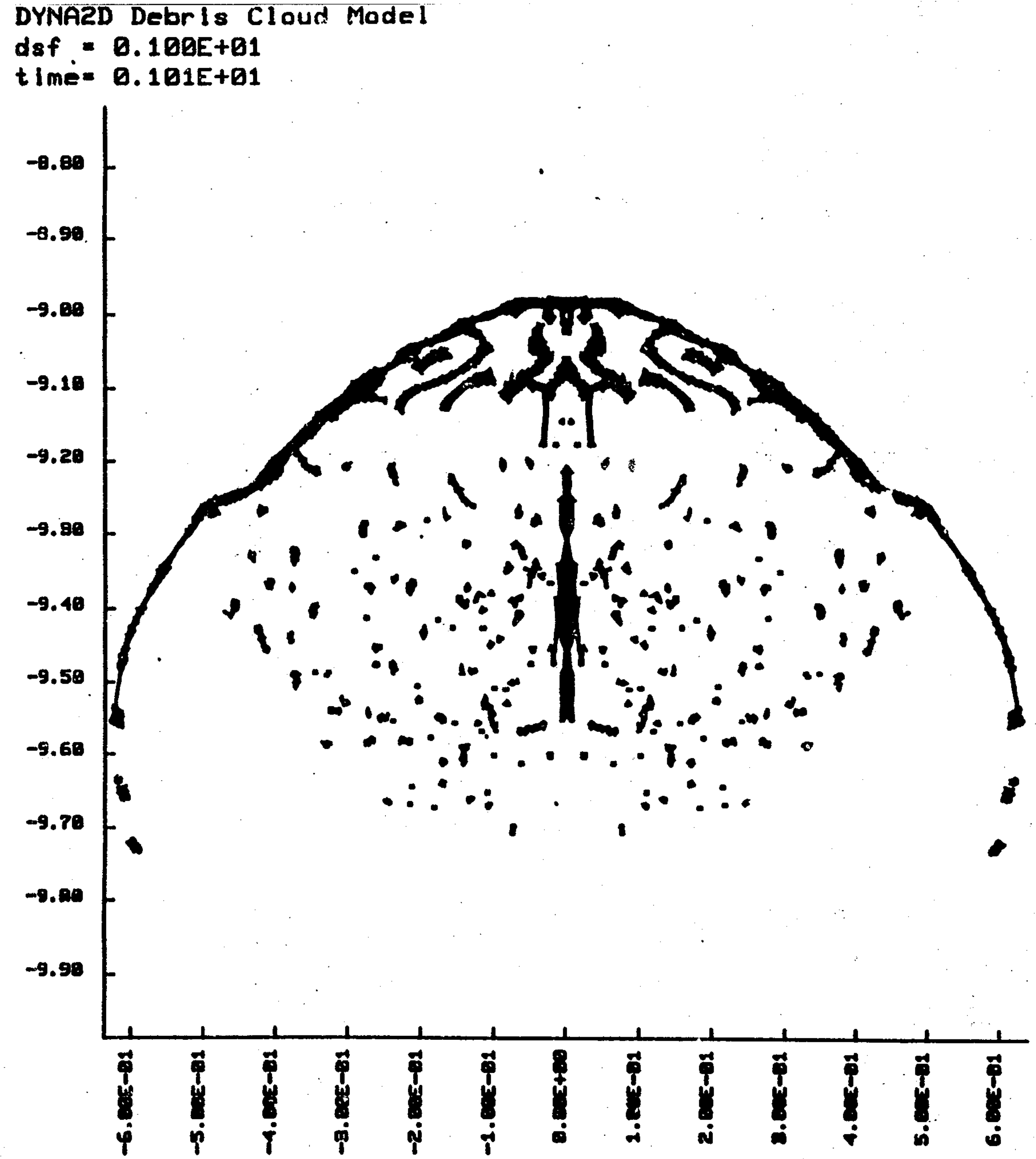
DYNA2D Debris Cloud Model
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time= 0.101E+01
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-8.90
-9.00
-9.10
-9.20
-9.30
-9.40
-9.50
-9.60
-9.70
-9.80
-9.90
-6.00E-01
-5.00E-01
-4.00E-01
-3.00E-01
-2.00E-01
-1.00E-01
0.00E+00
1.00E-01
2.00E-01
3.00E-01
4.00E-01
5.00E-01
6.00E-01

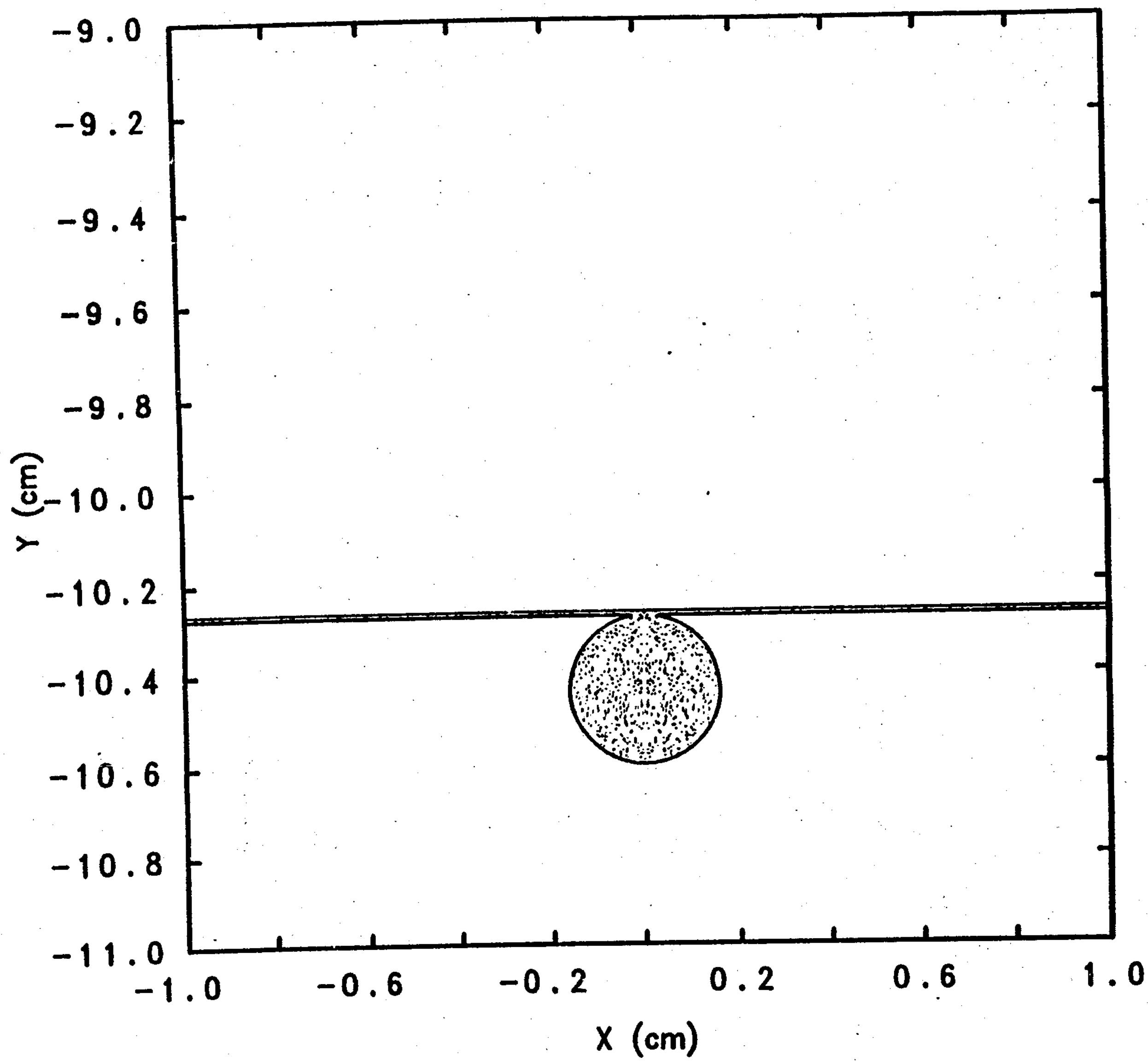
t = 2.5 μsec

APPENDIX B

Legend

Density (g/cm^3)

- 7.500E-01
- 1.500E+00
- 3.000E+00
- 6.000E+00
- 1.200E+01



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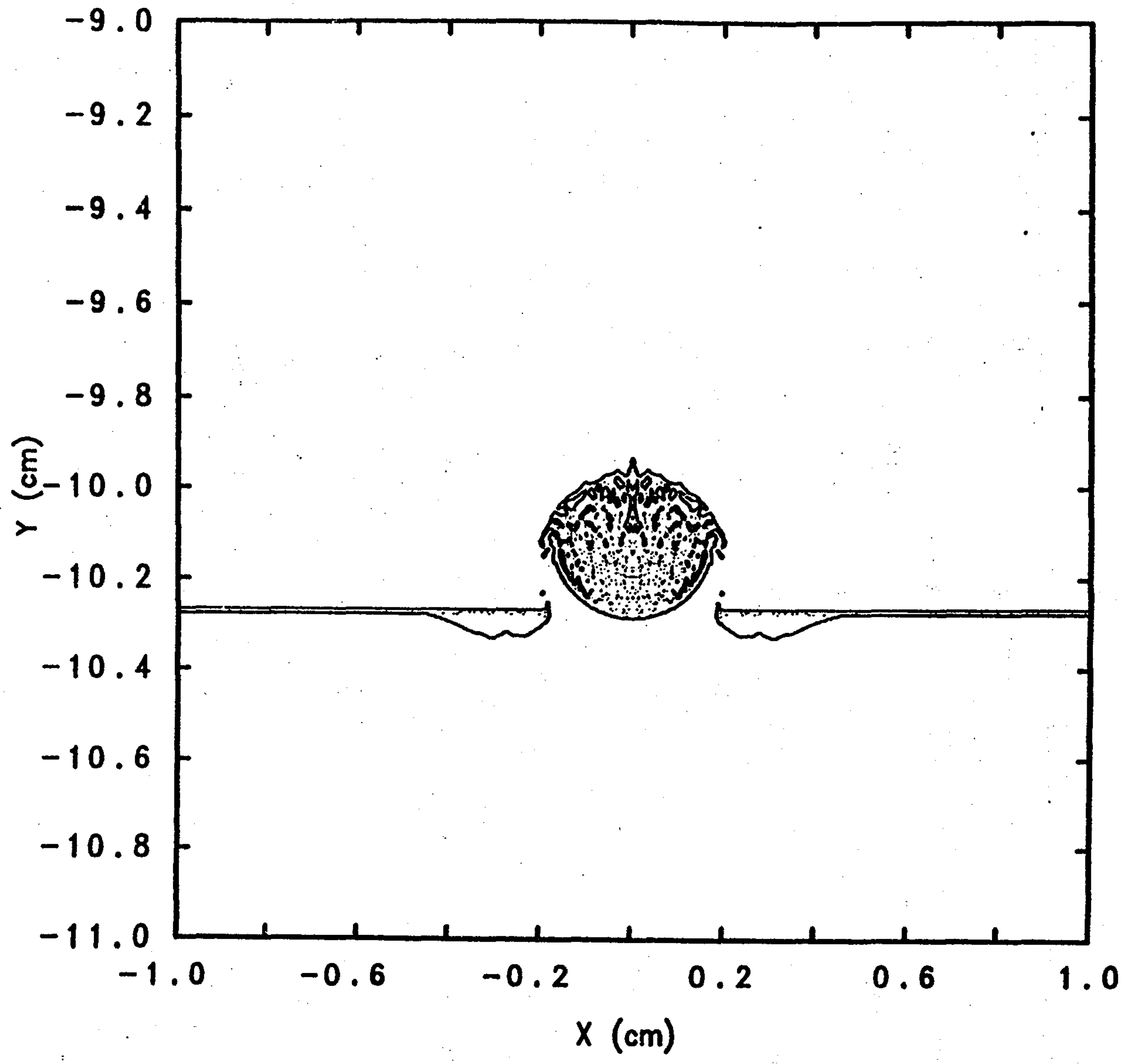

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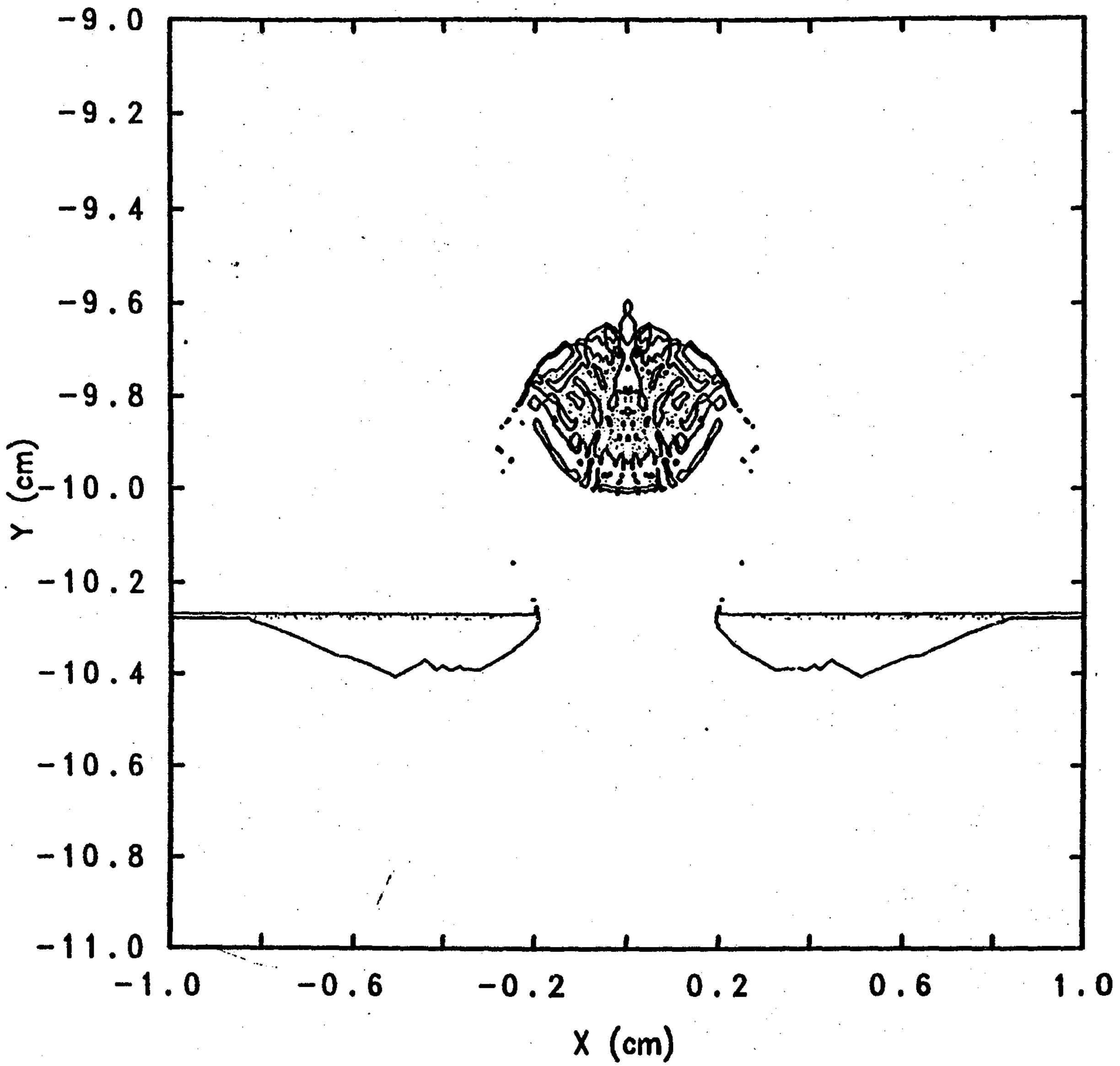

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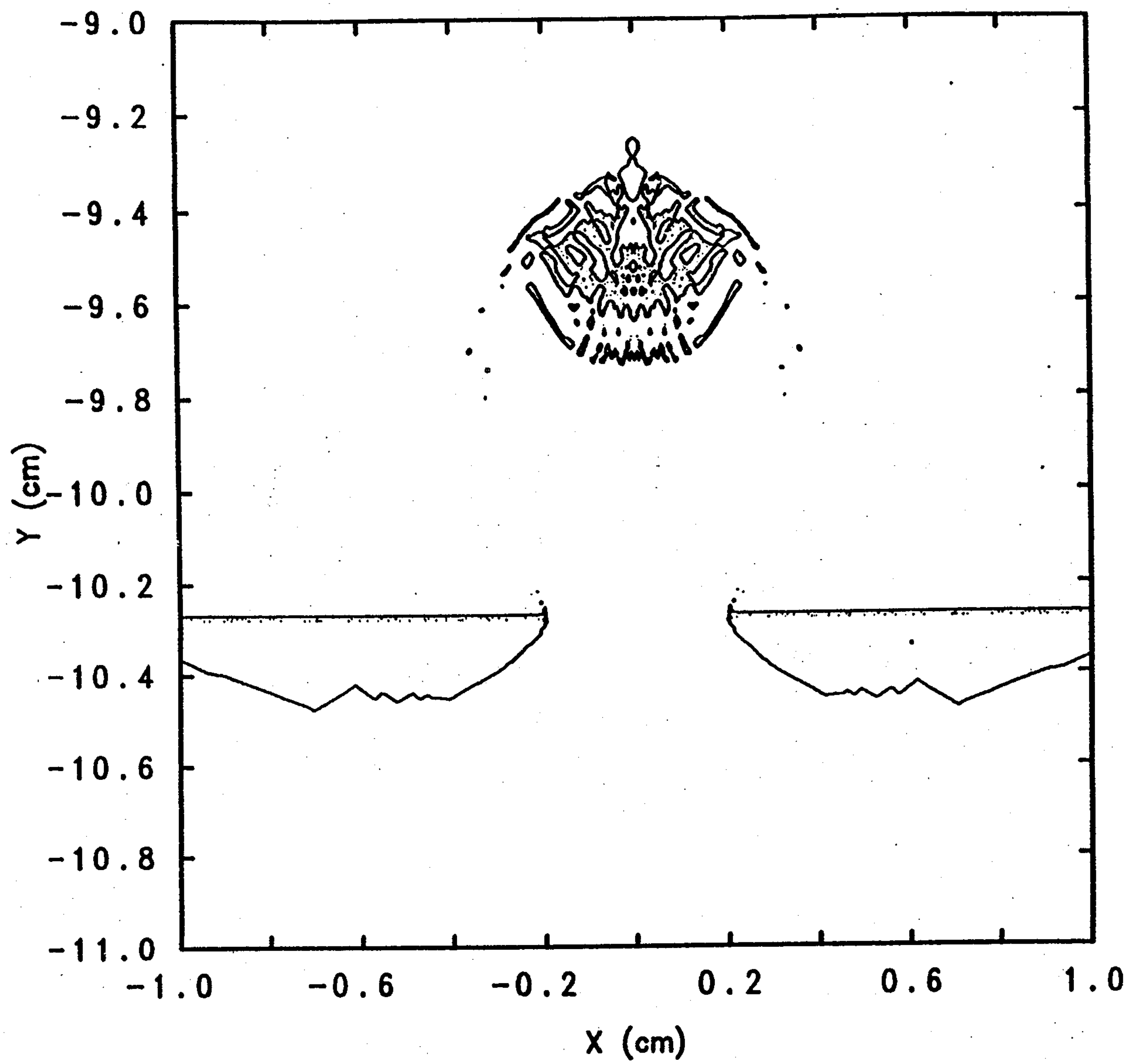

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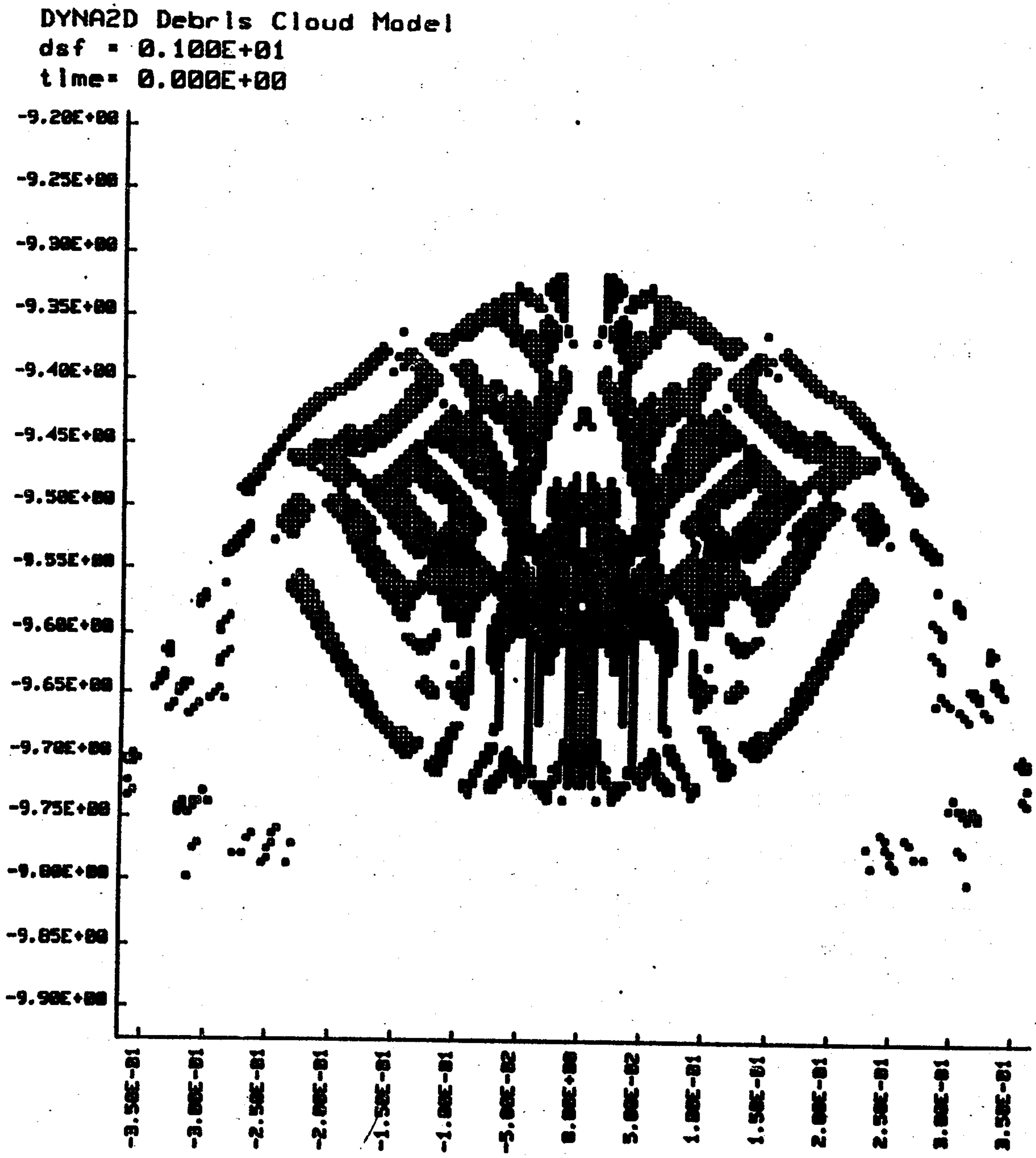
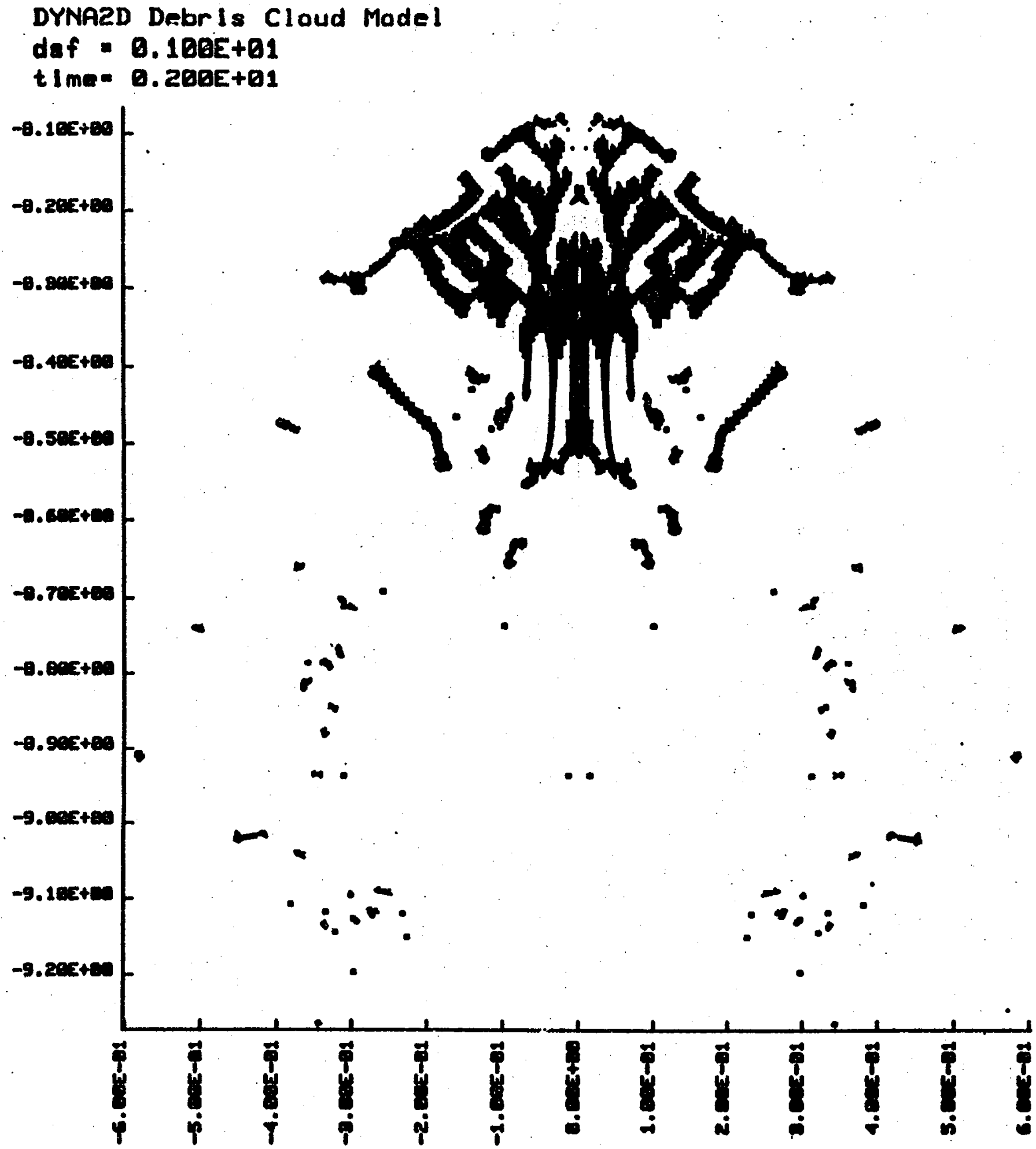

DYNA2D Debris Cloud Model
dsf = 0.100E+01
time= 0.000E+00
-9.20E+00
-9.25E+00
-9.30E+00
-9.35E+00
-9.40E+00
-9.45E+00
-9.50E+00
-9.55E+00
-9.60E+00
-9.65E+00
-9.70E+00
-9.75E+00
-9.80E+00
-9.85E+00
-9.90E+00
-3.50E-01
-3.00E-01
-2.50E-01
-2.00E-01
-1.50E-01
-1.00E-01
-5.00E-02
0.00E+00
5.00E-02
1.00E-01
1.50E-01
2.00E-01
2.50E-01
3.00E-01
3.50E-01

t=1.5 µsec



t = 3.5 µsec

APPENDIX C

Legend

Density (g/cm^3)

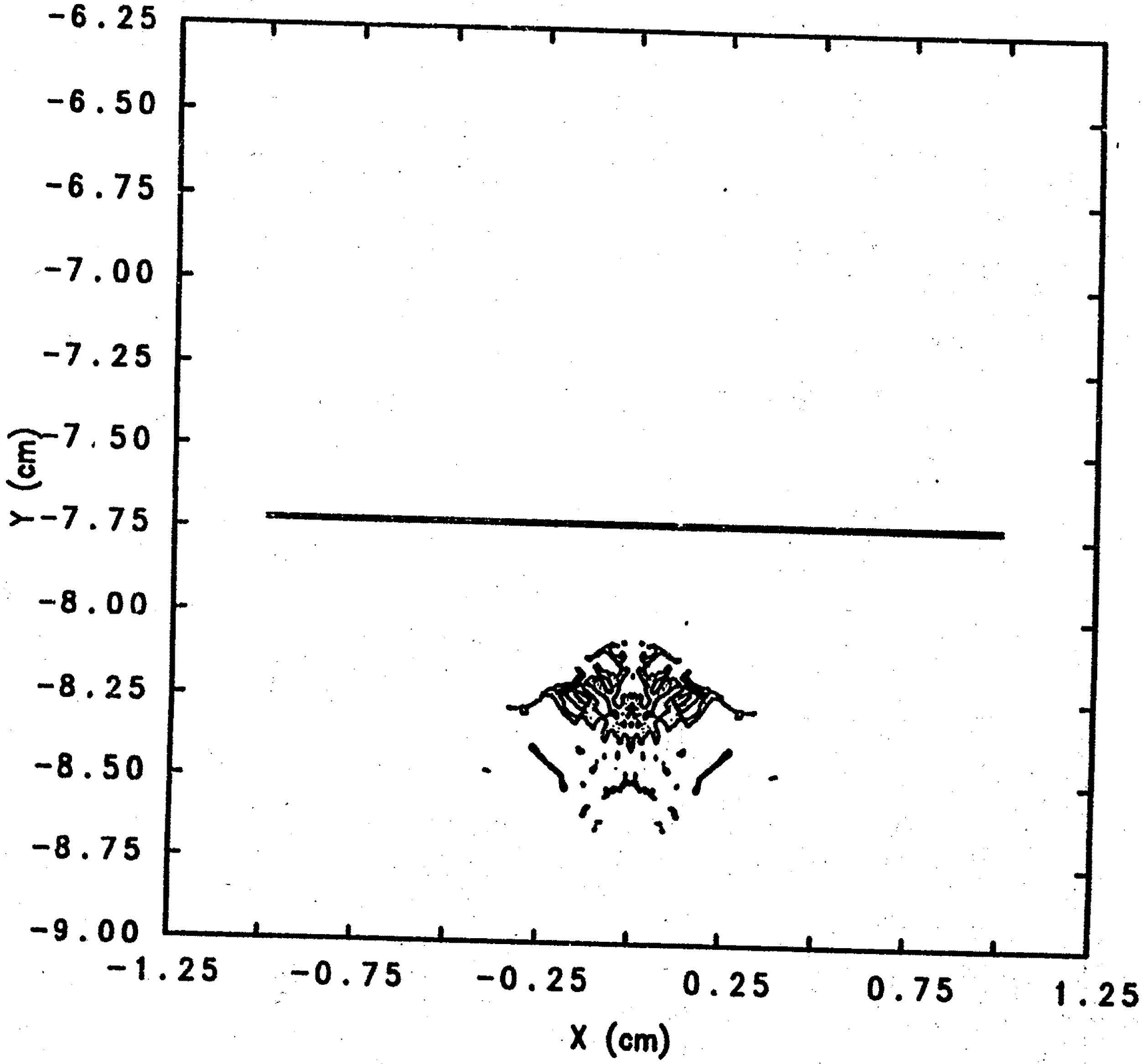
7.500E-01

1.500E+00

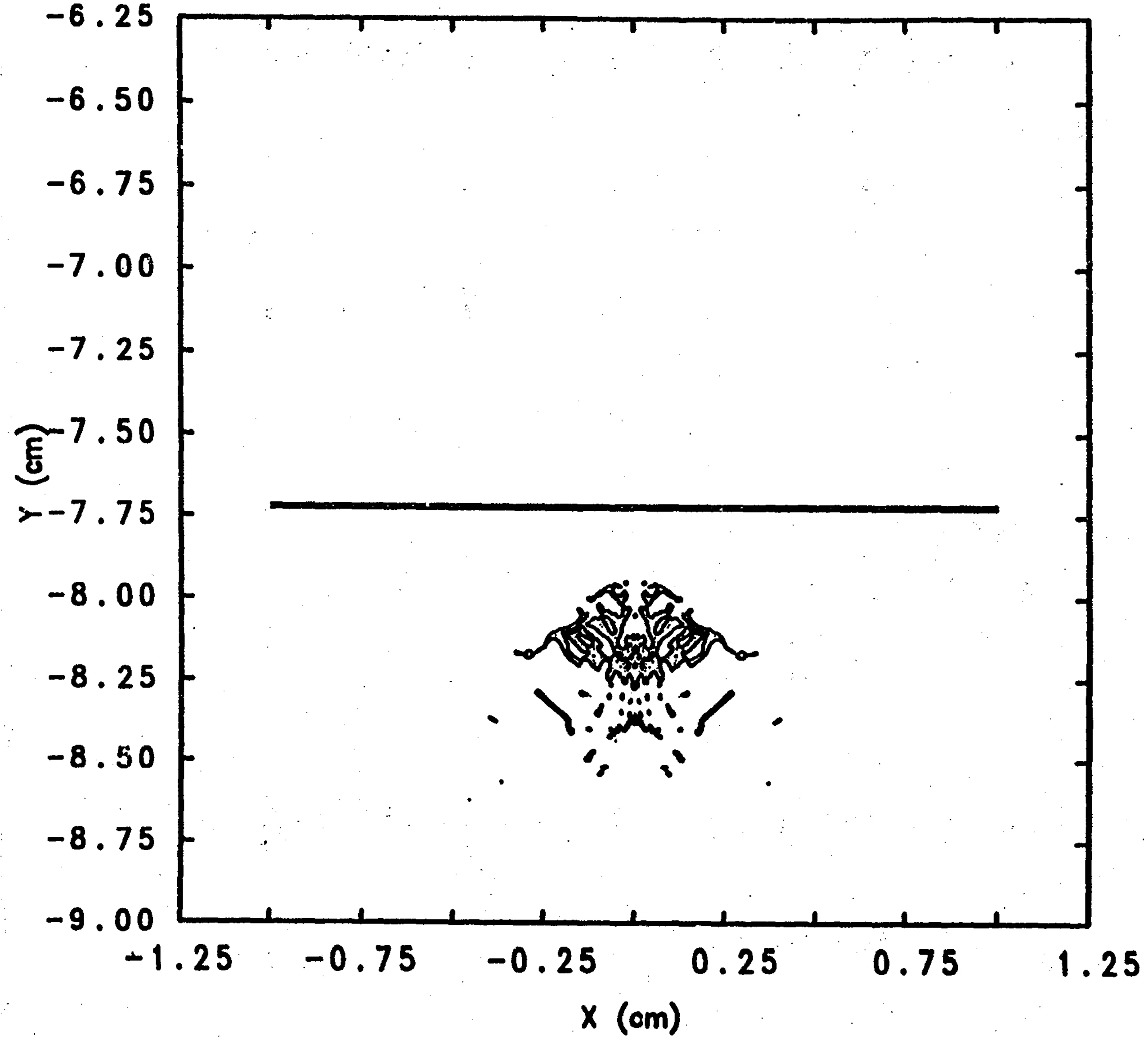
3.000E+00

6.000E+00

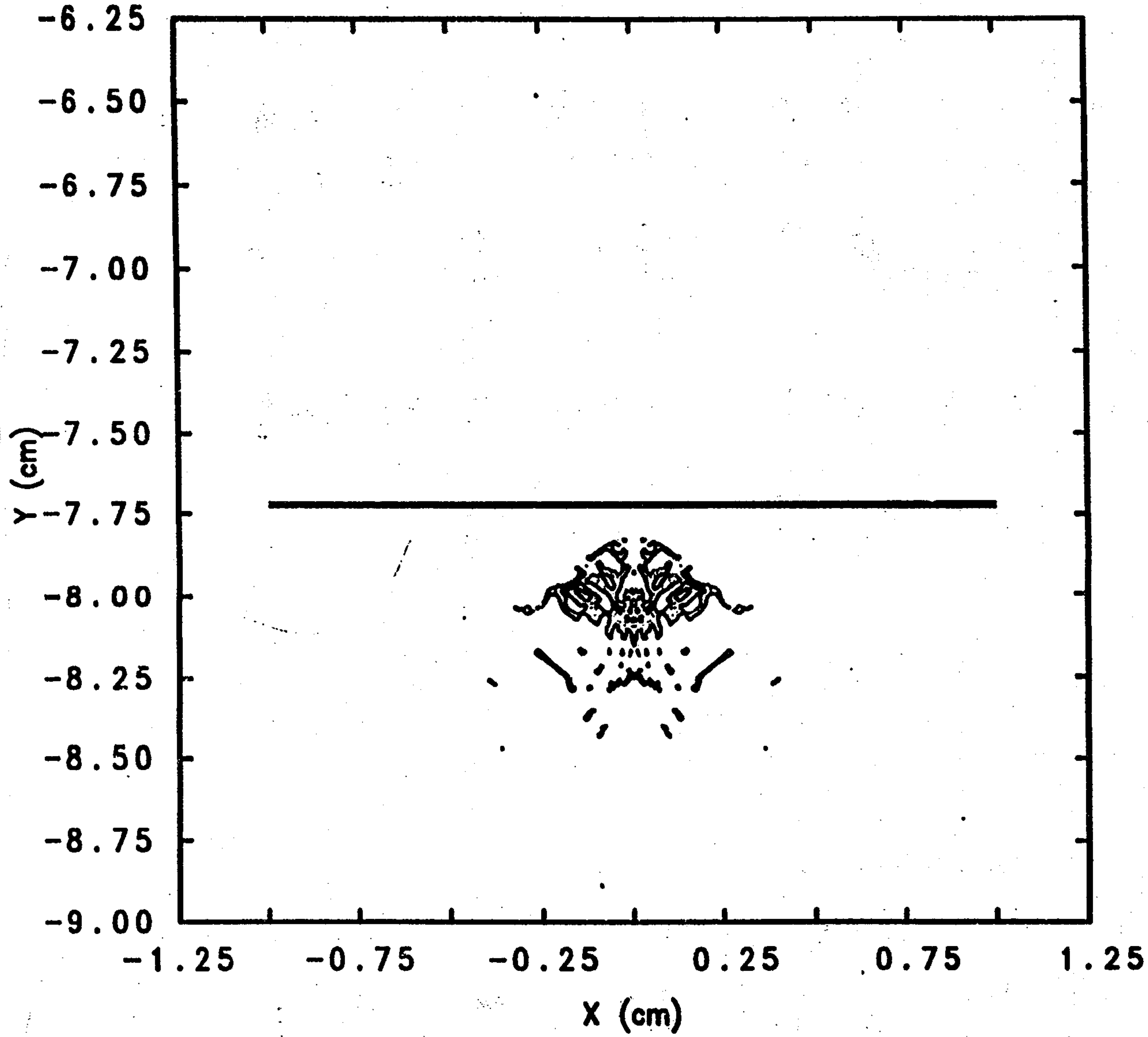
1.200E+01


-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

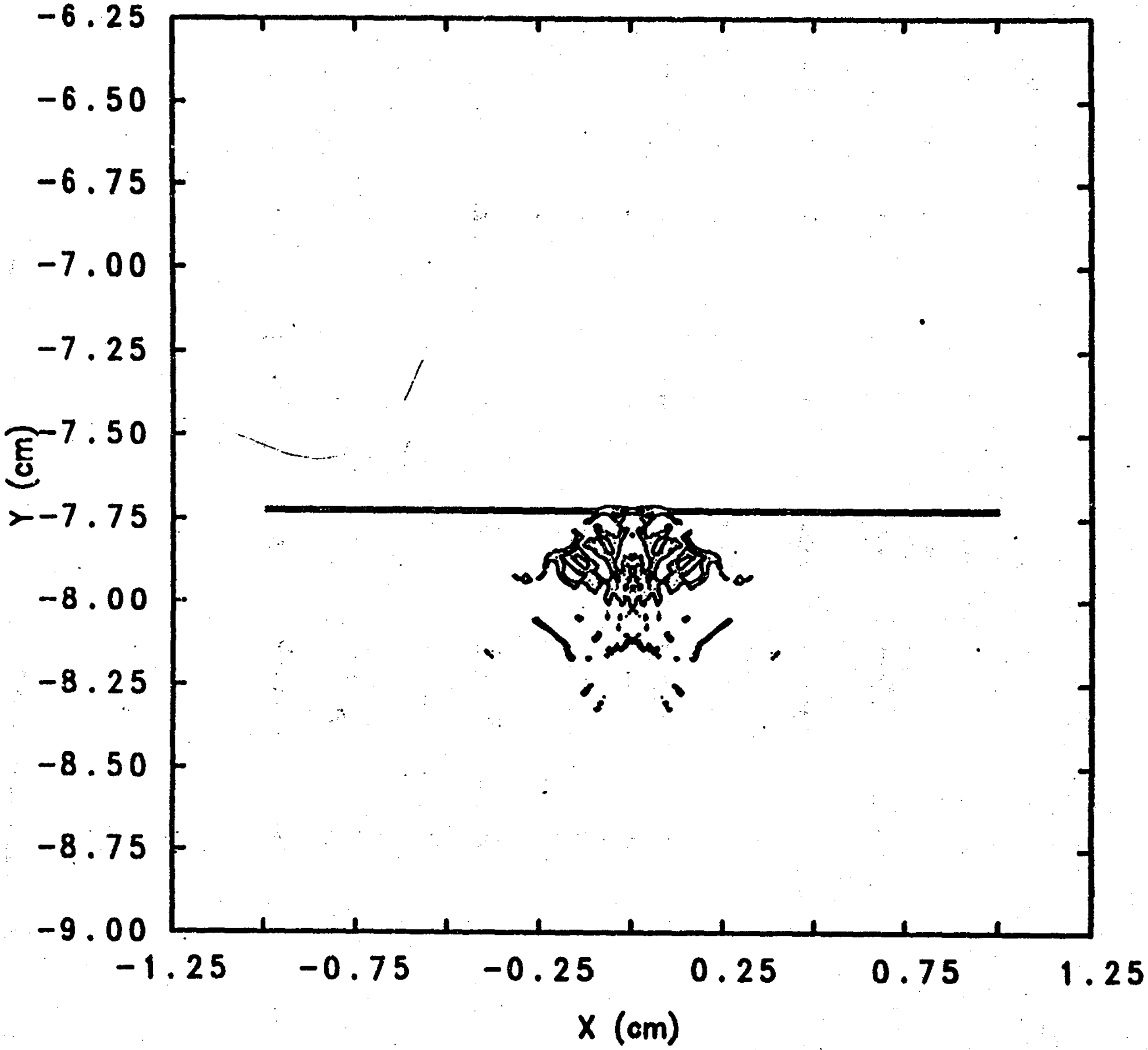
t = 3.5 µsec


-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t=3.7 μsec

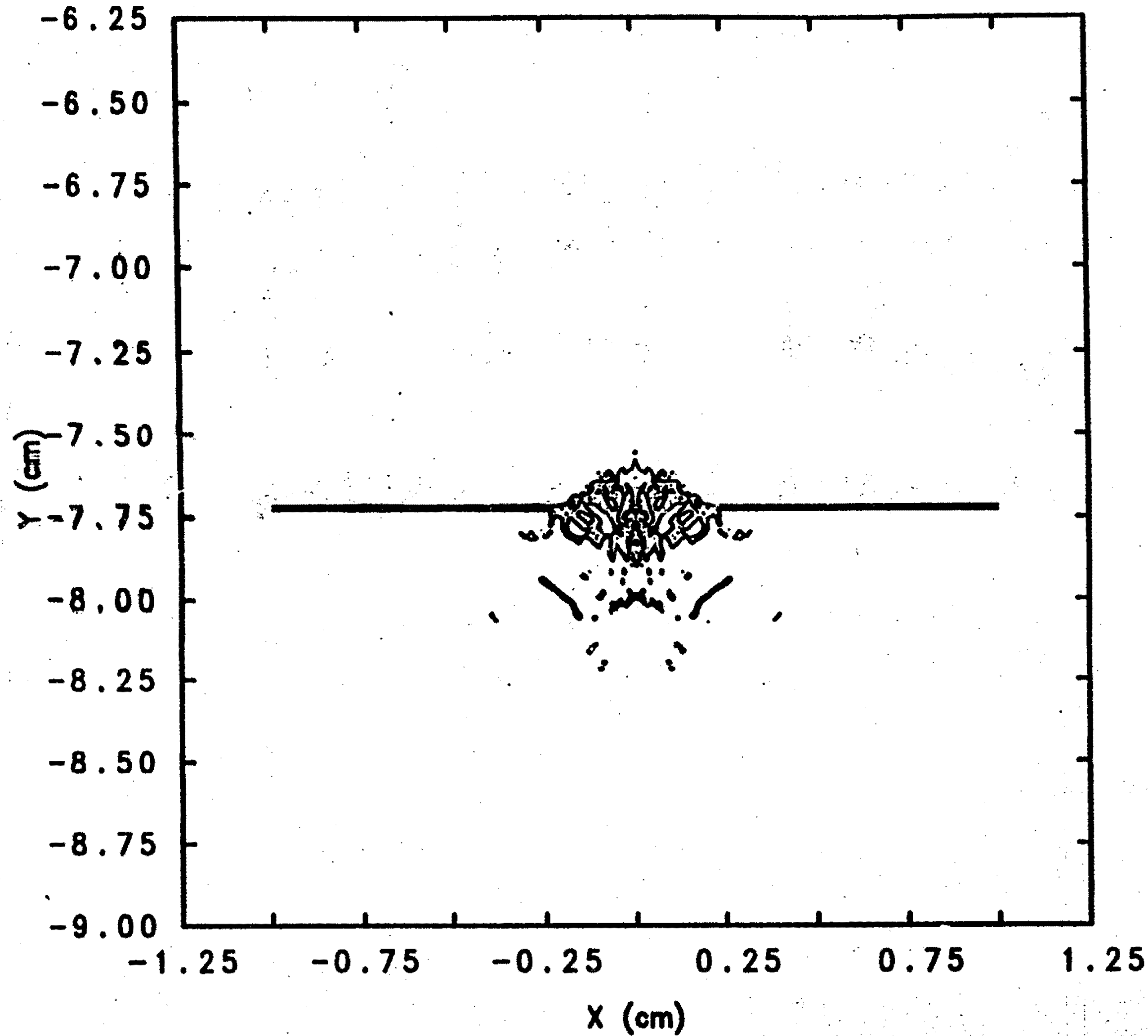

-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 3.9 µsec.

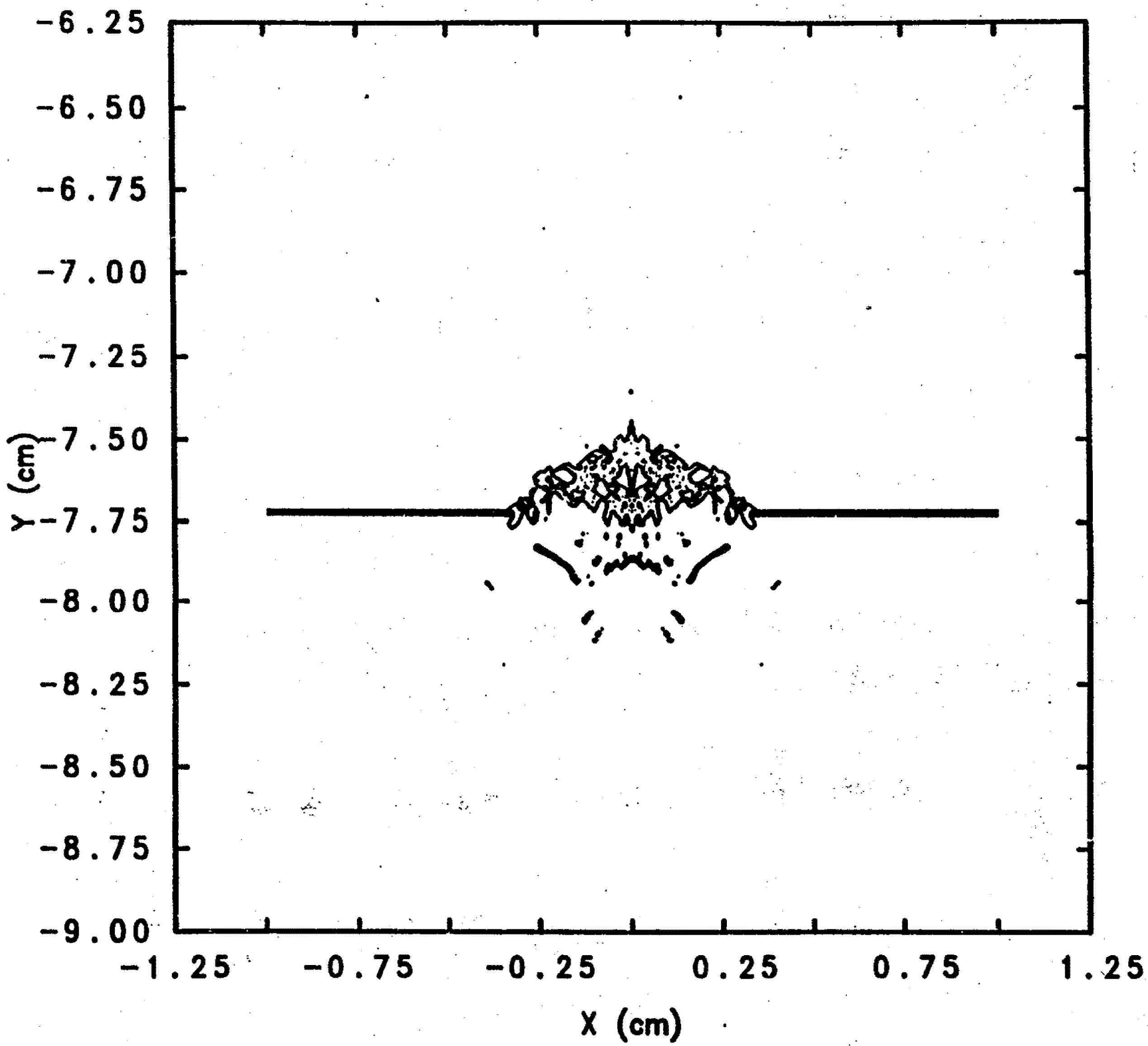


-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

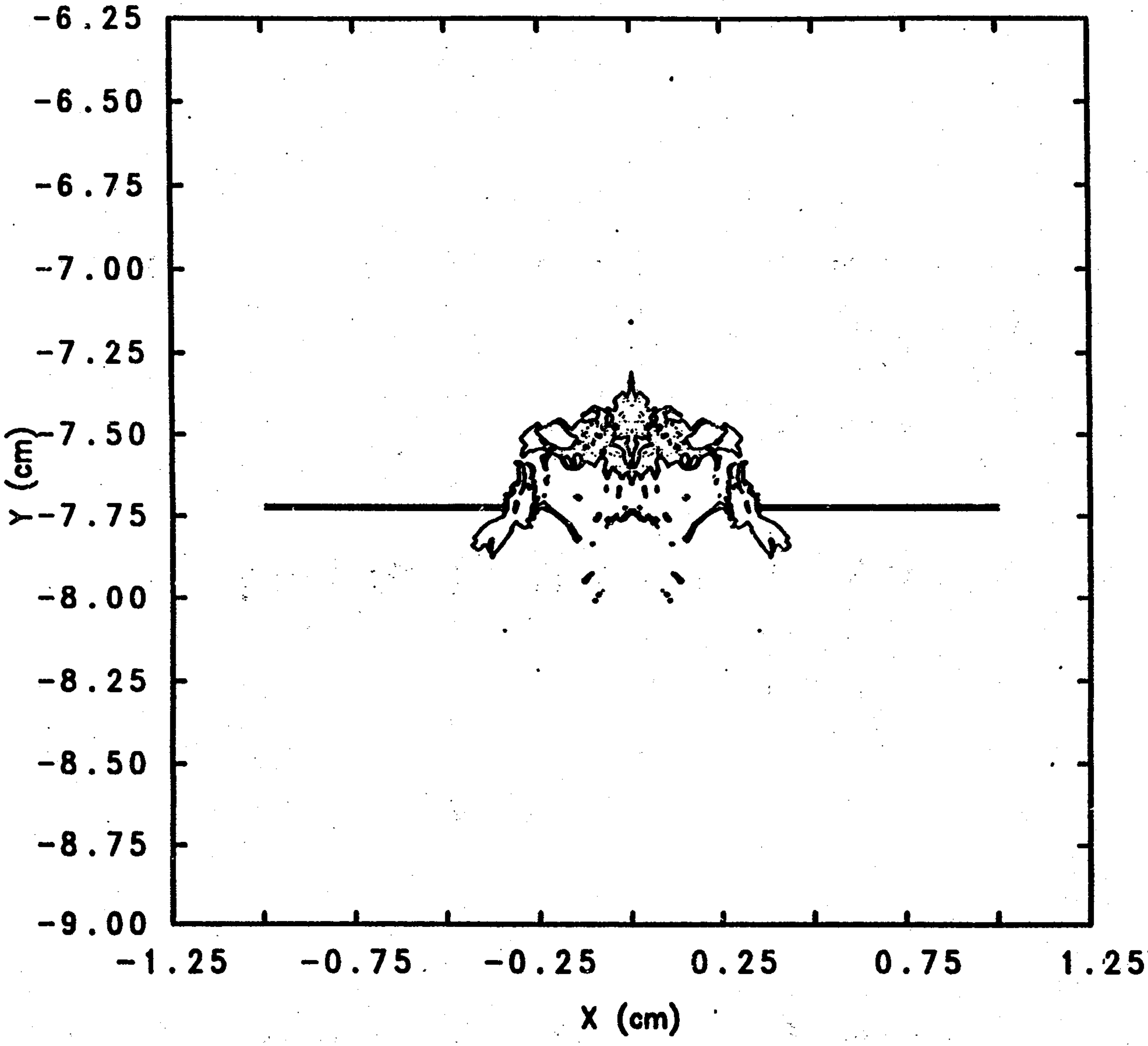
t = 4.1 μsec


-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

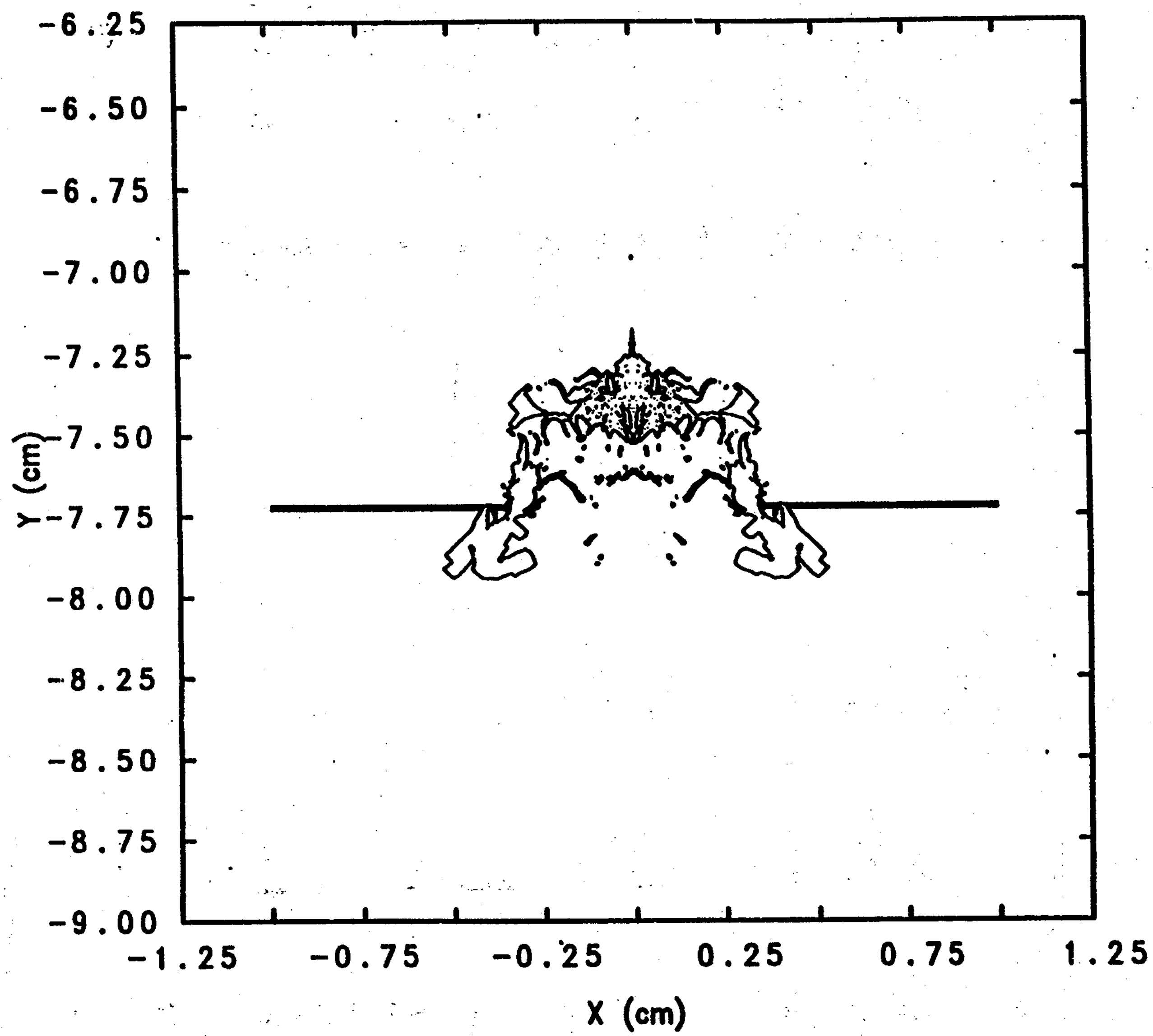
t = 4.3 μsec


-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

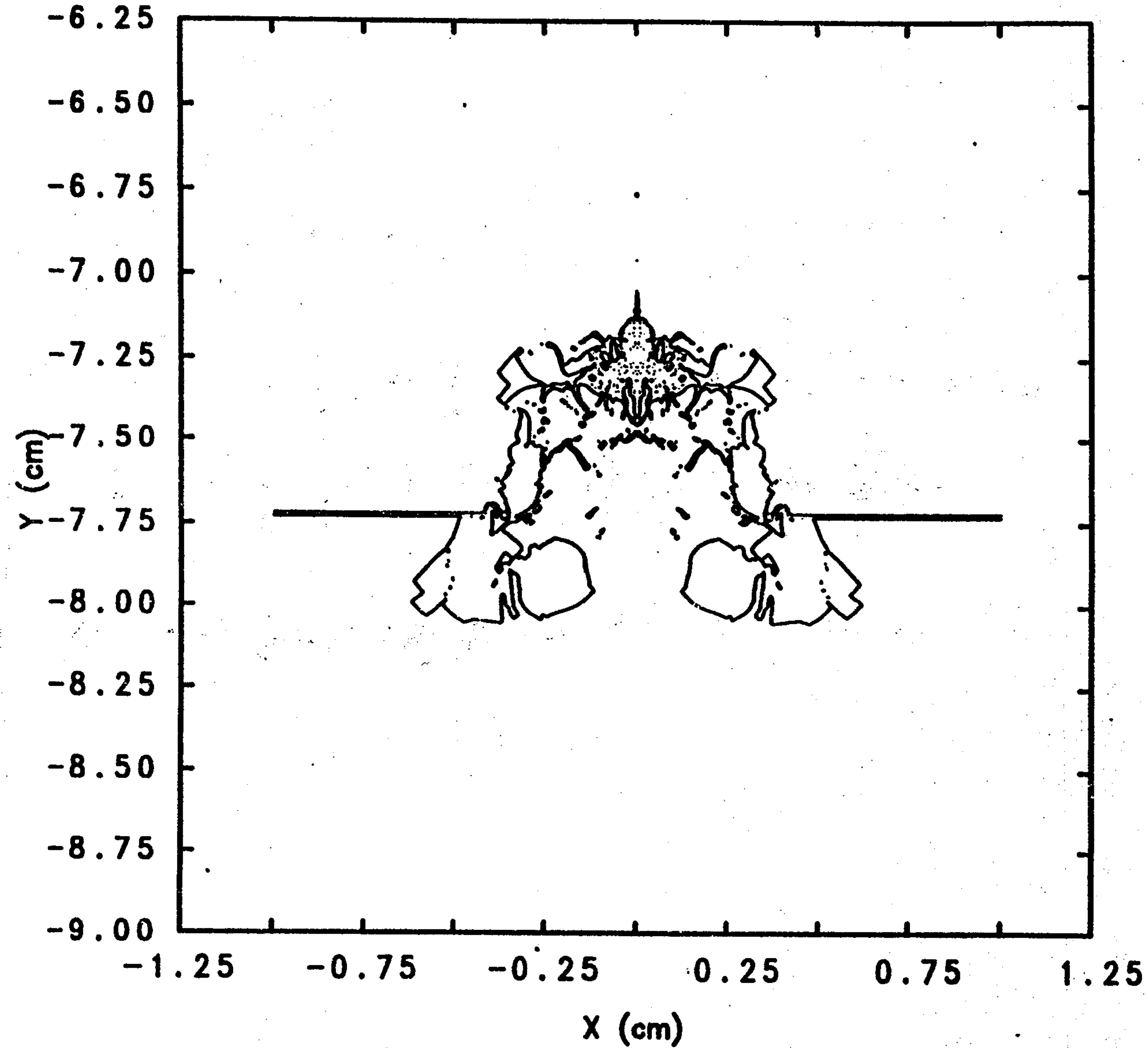
t = 4.5 μsec


-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t=4.7 μsec


-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t=4.9 μsec


-6.25
-6.50
-6.75
-7.00
-7.25
-7.50
-7.75
-8.00
-8.25
-8.50
-8.75
-9.00
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t=5.1 μsec

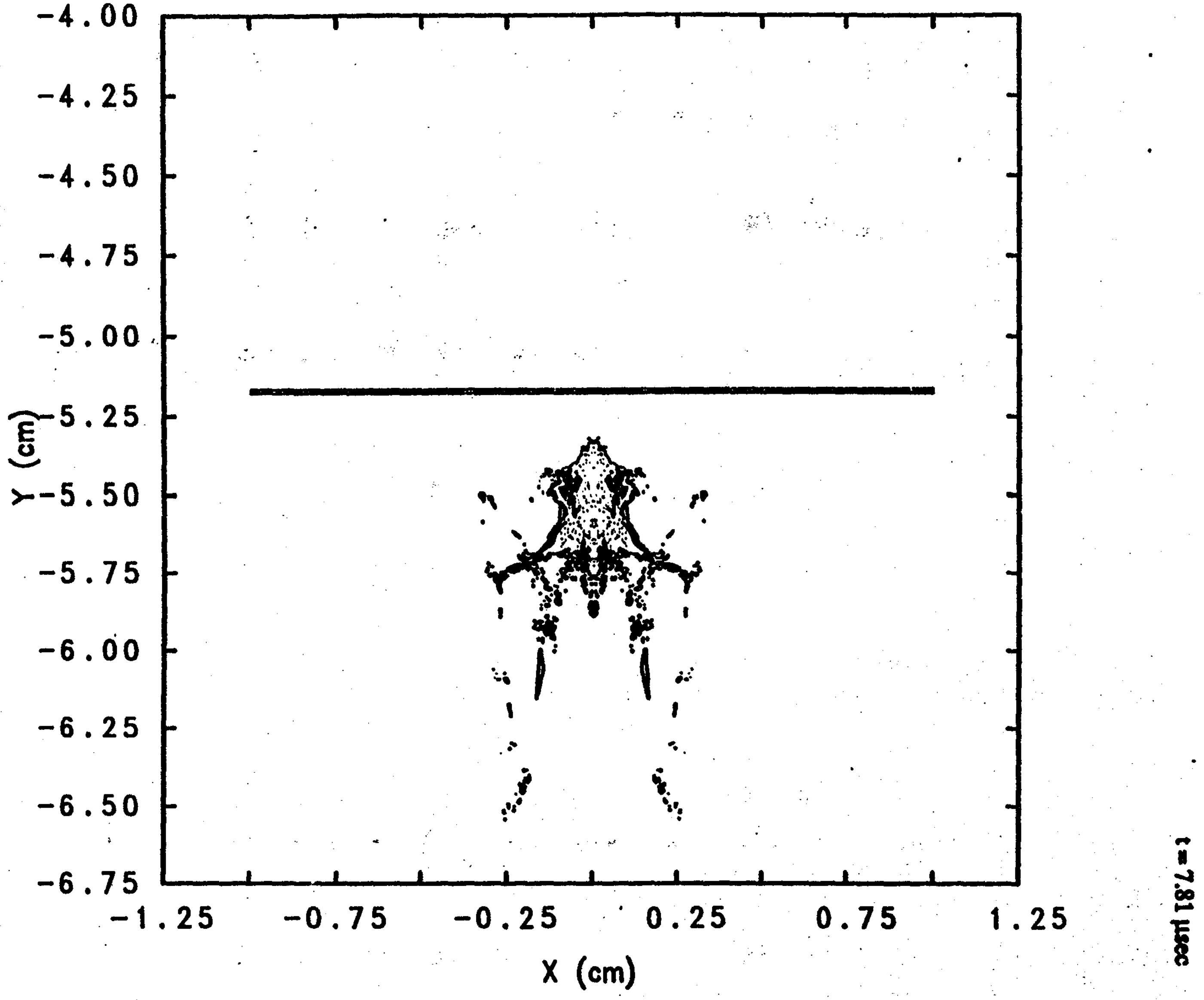
C-11

APPENDIX D

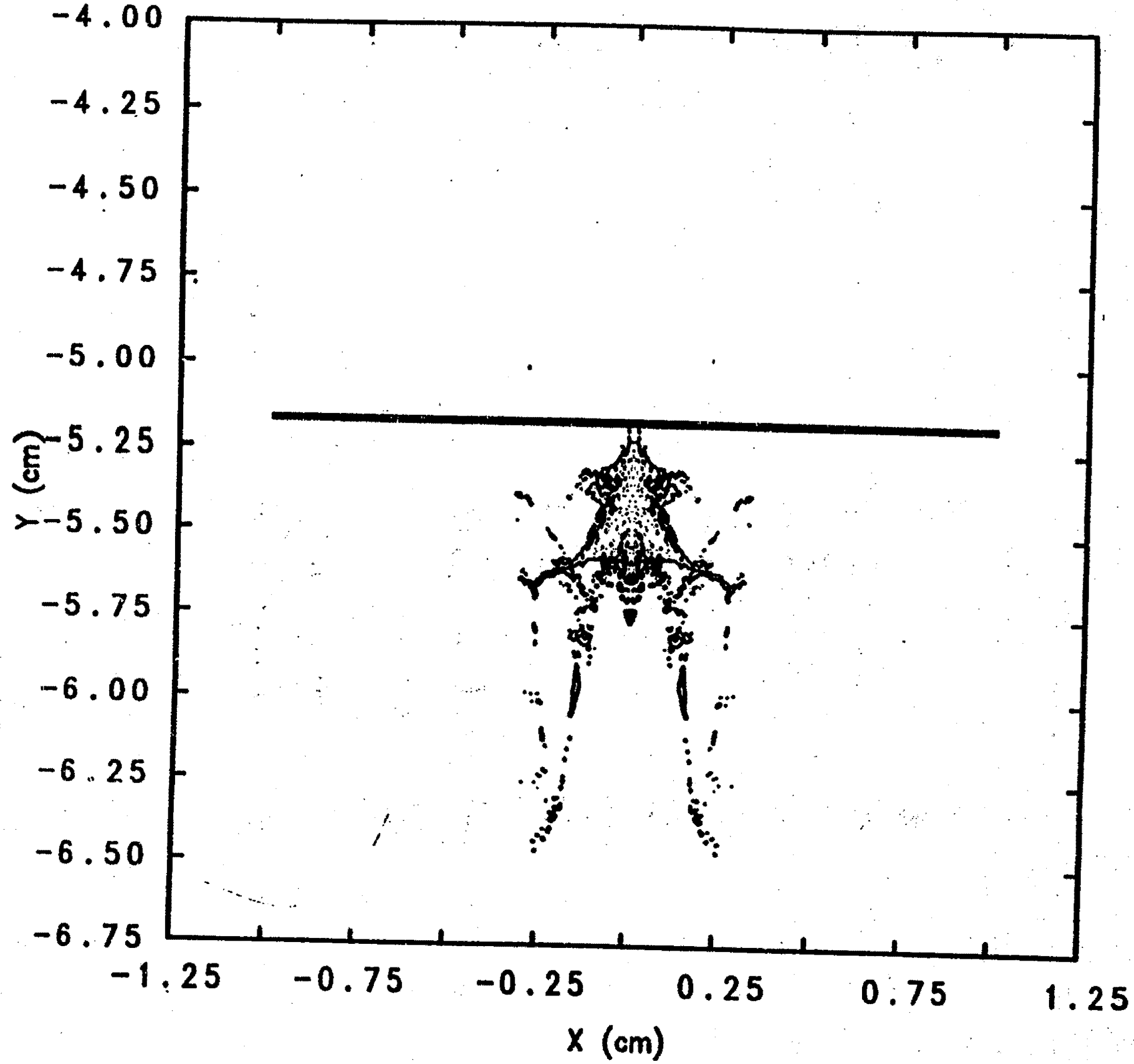
Legend

Density (g/cm³)

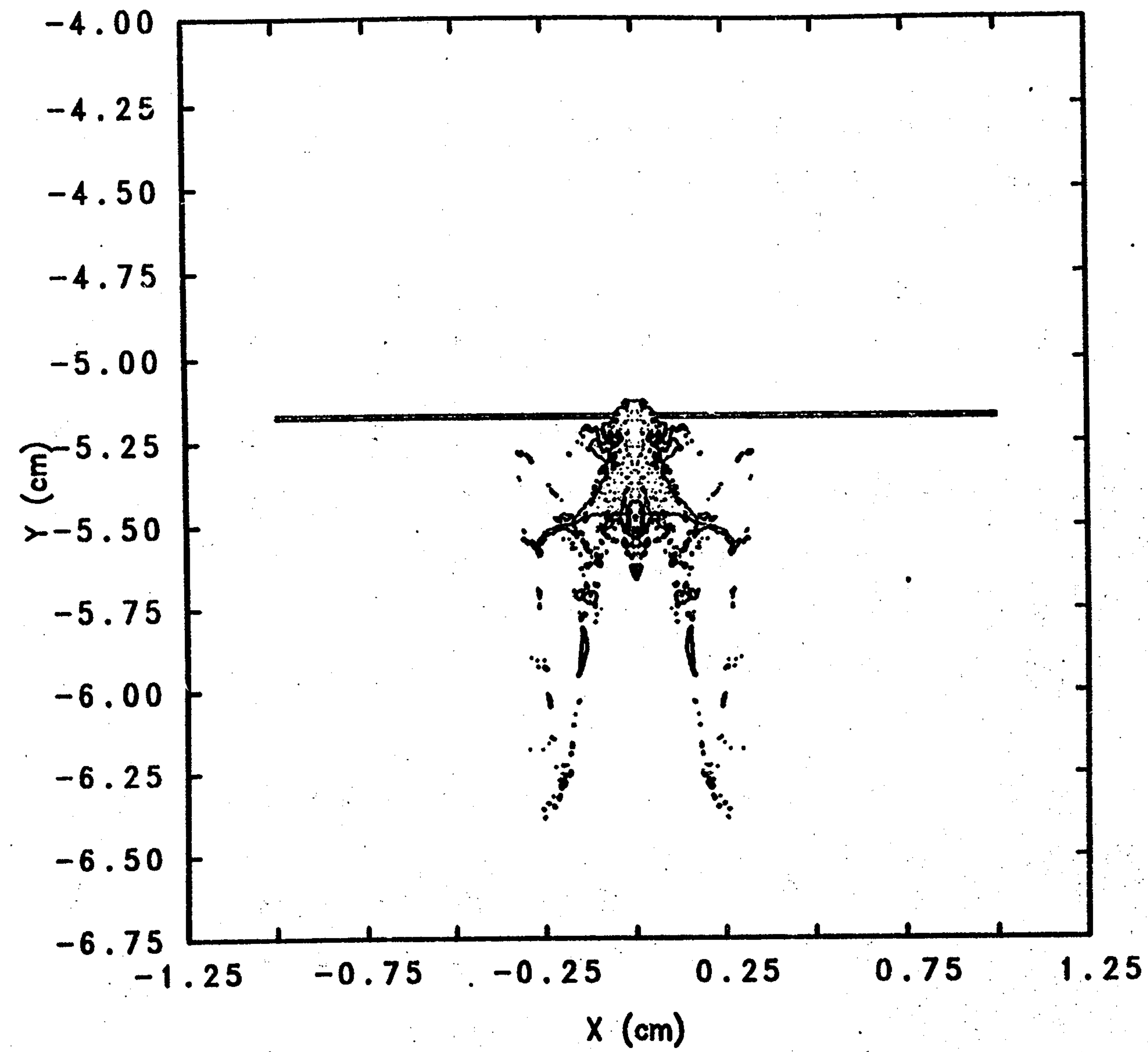
	7.500E-01
	1.500E+00
	3.000E+00
	6.000E+00
	1.200E+01



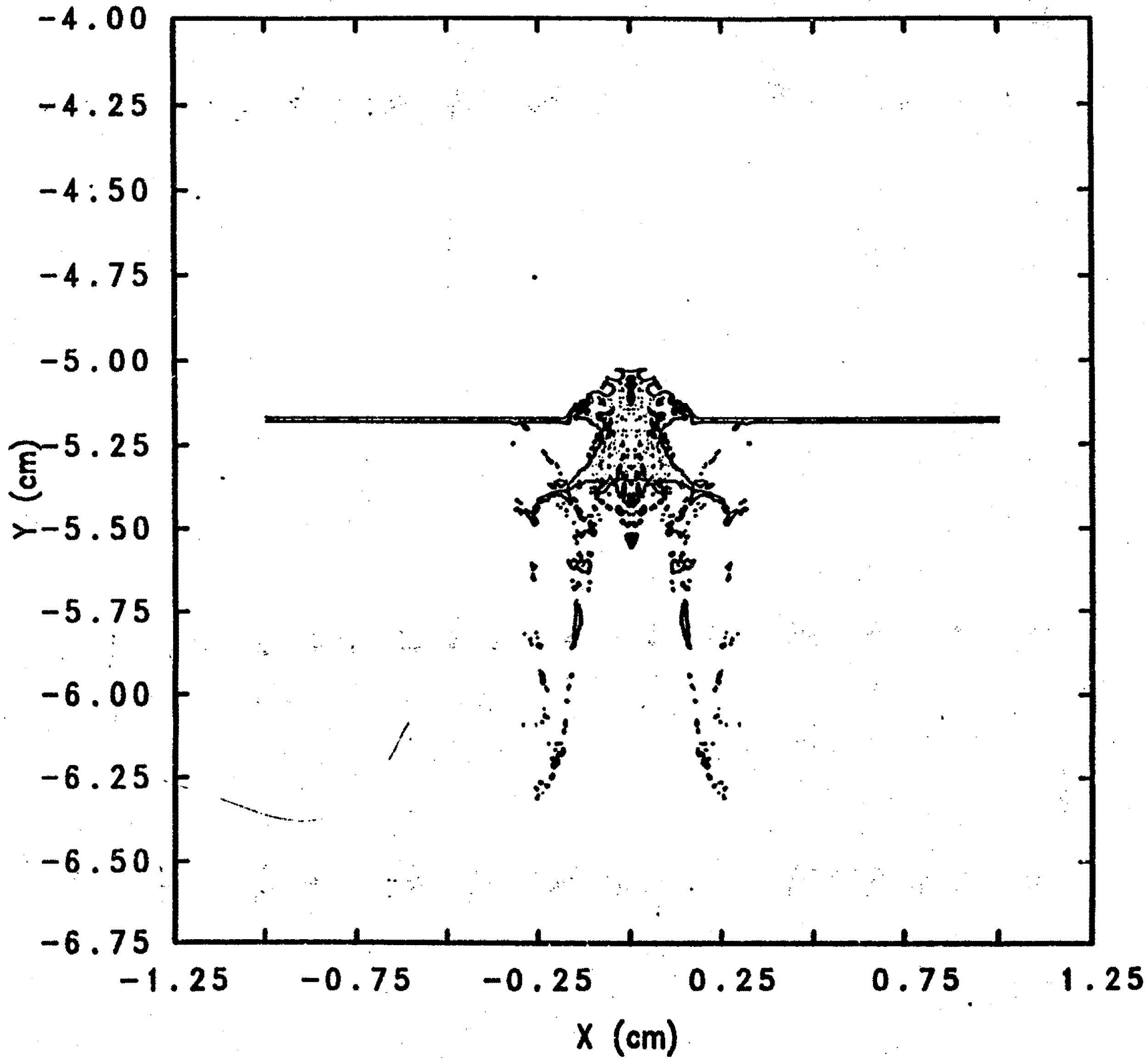
-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)
t=7.81 µsec


-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

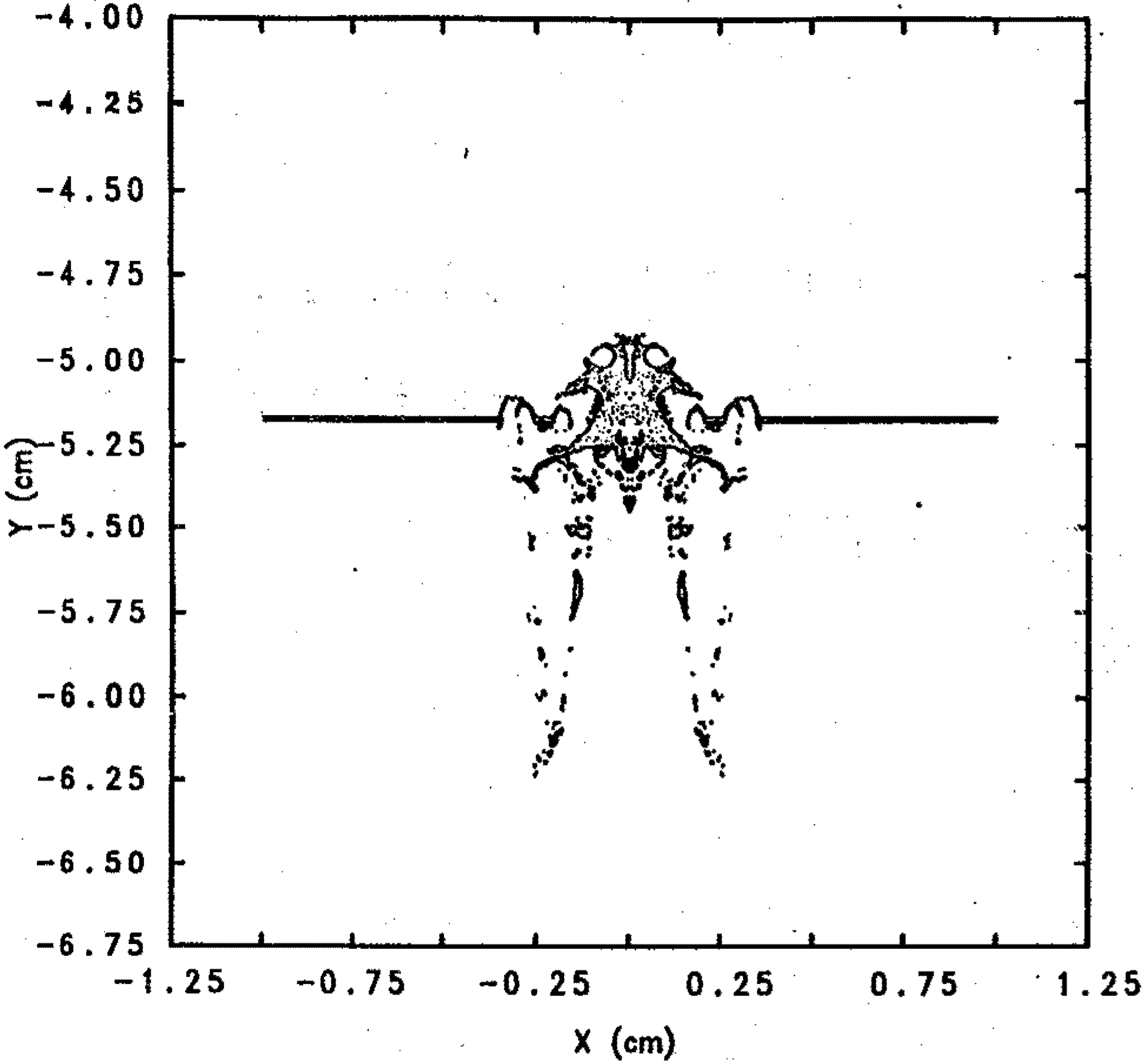
t = 8.01 μsec


-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

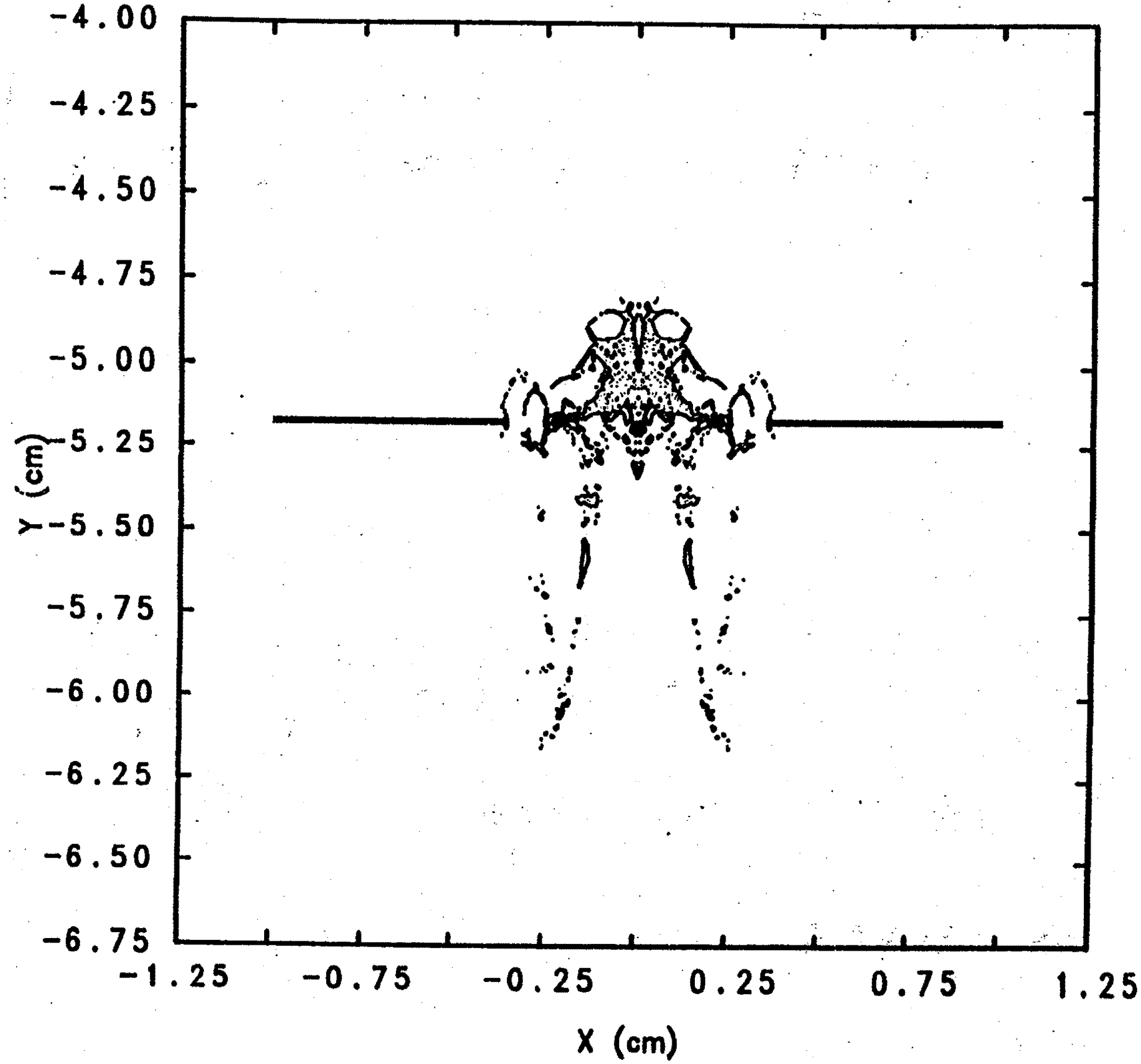
t = 8.21 μsec


-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

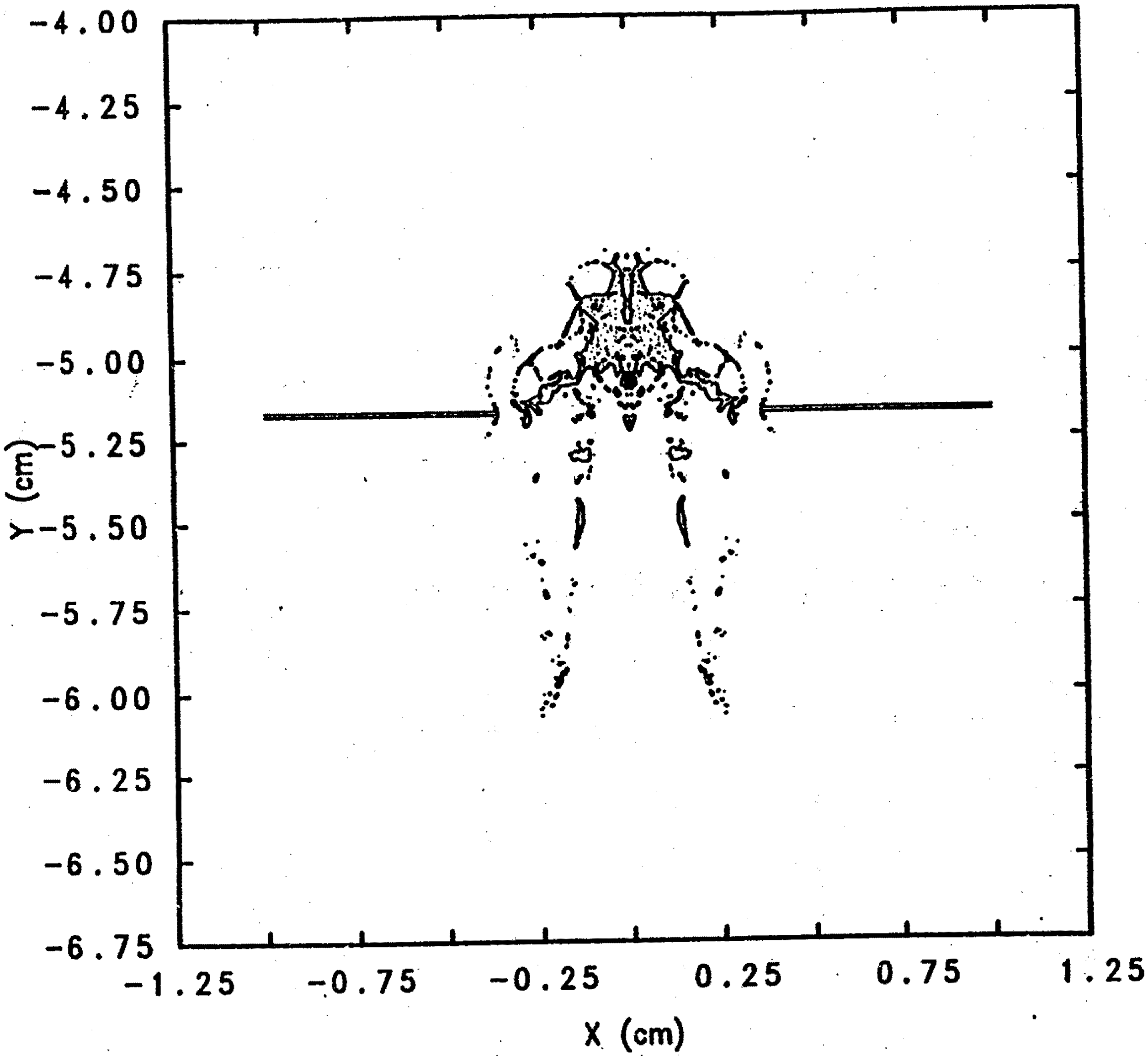
t = 8.41 μsec


-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 8.61 μsec

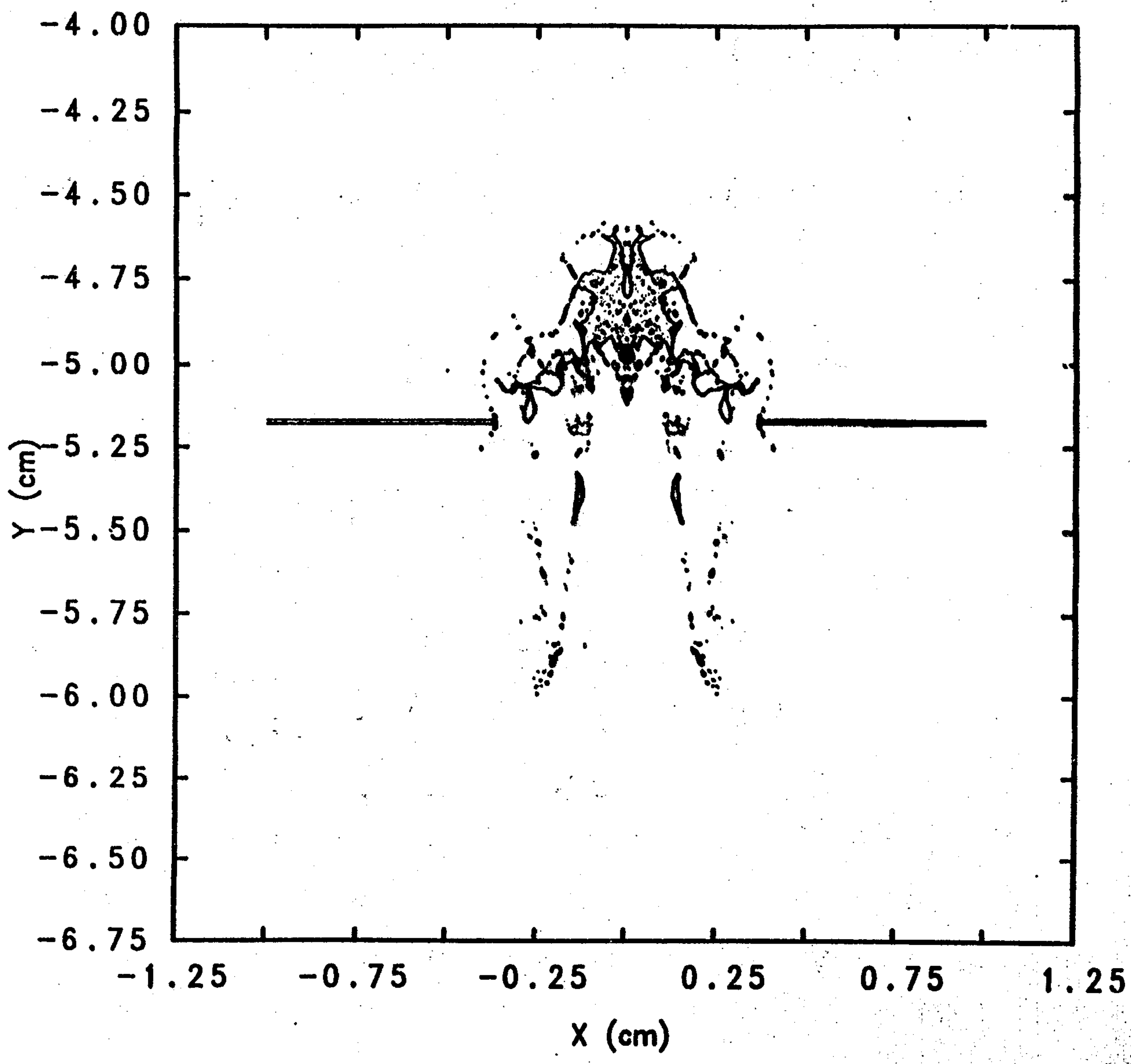

-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 8.81 μsec

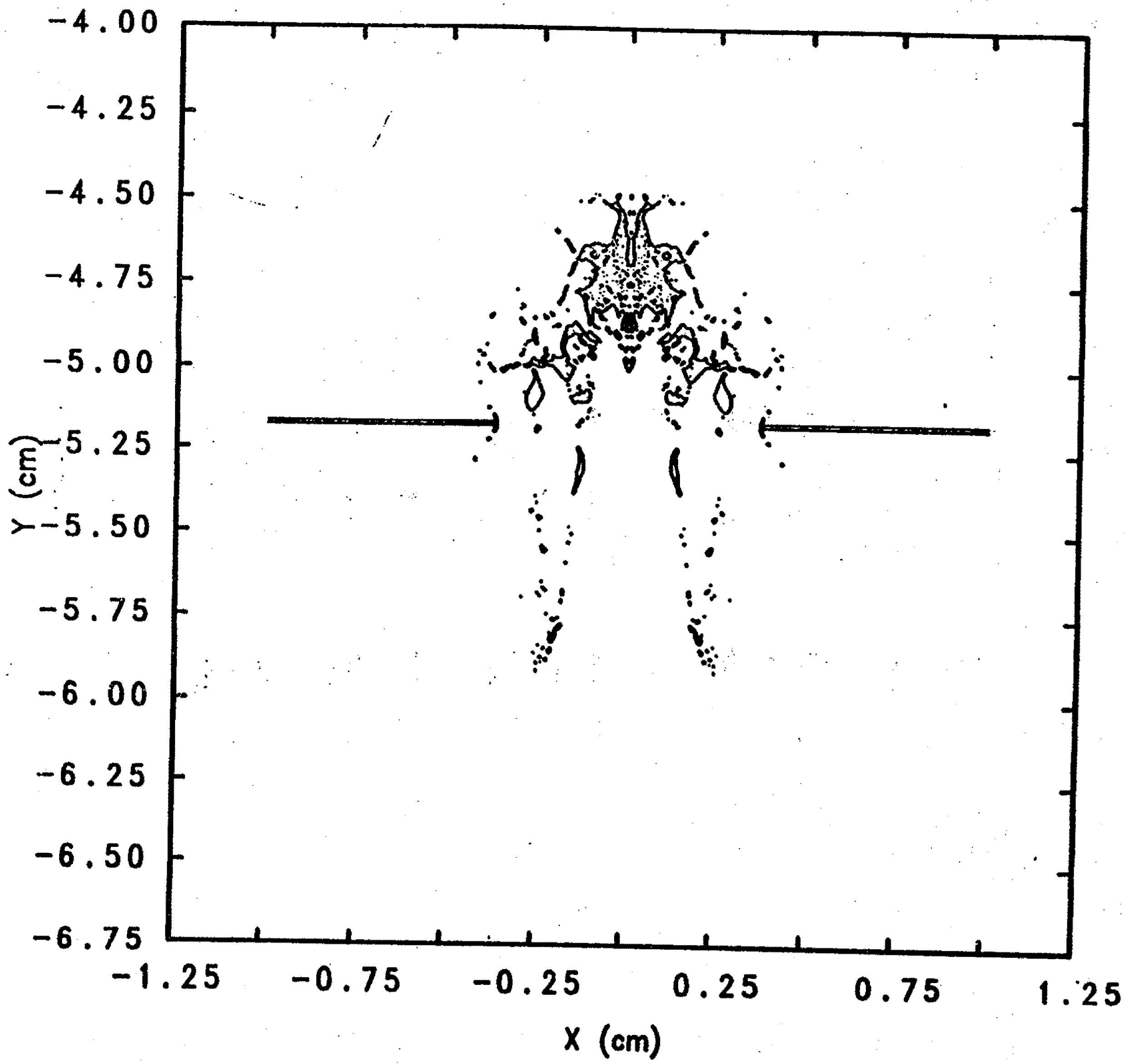


-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 9.01 μsec


-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 9.21 µsec



-4.00
-4.25
-4.50
-4.75
-5.00
-5.25
-5.50
-5.75
-6.00
-6.25
-6.50
-6.75
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 9.41 μsec

APPENDIX E

Legend

Density (g/cm^3)

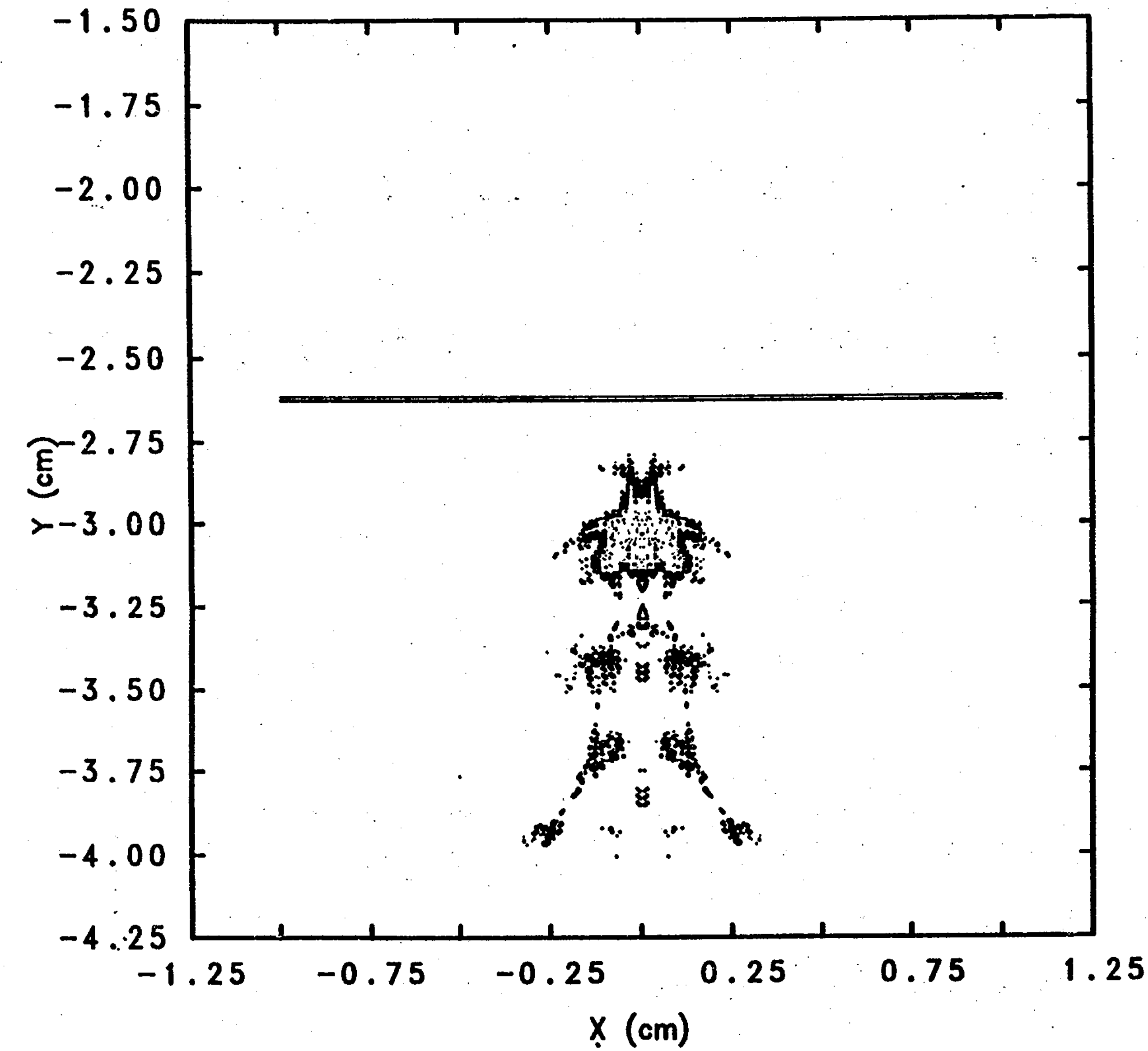
7.500E-01

1.500E+00

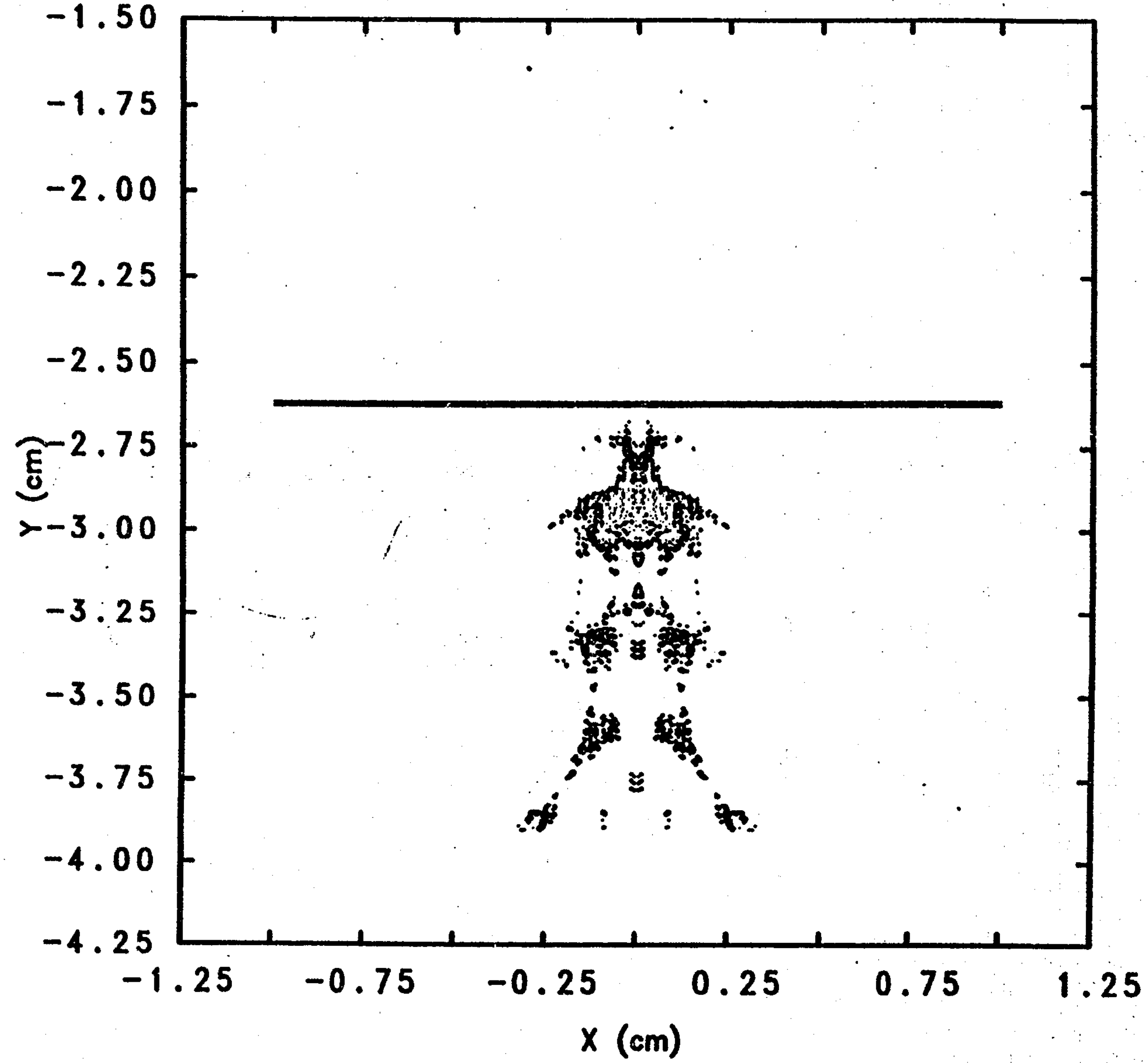
3.000E+00

6.000E+00

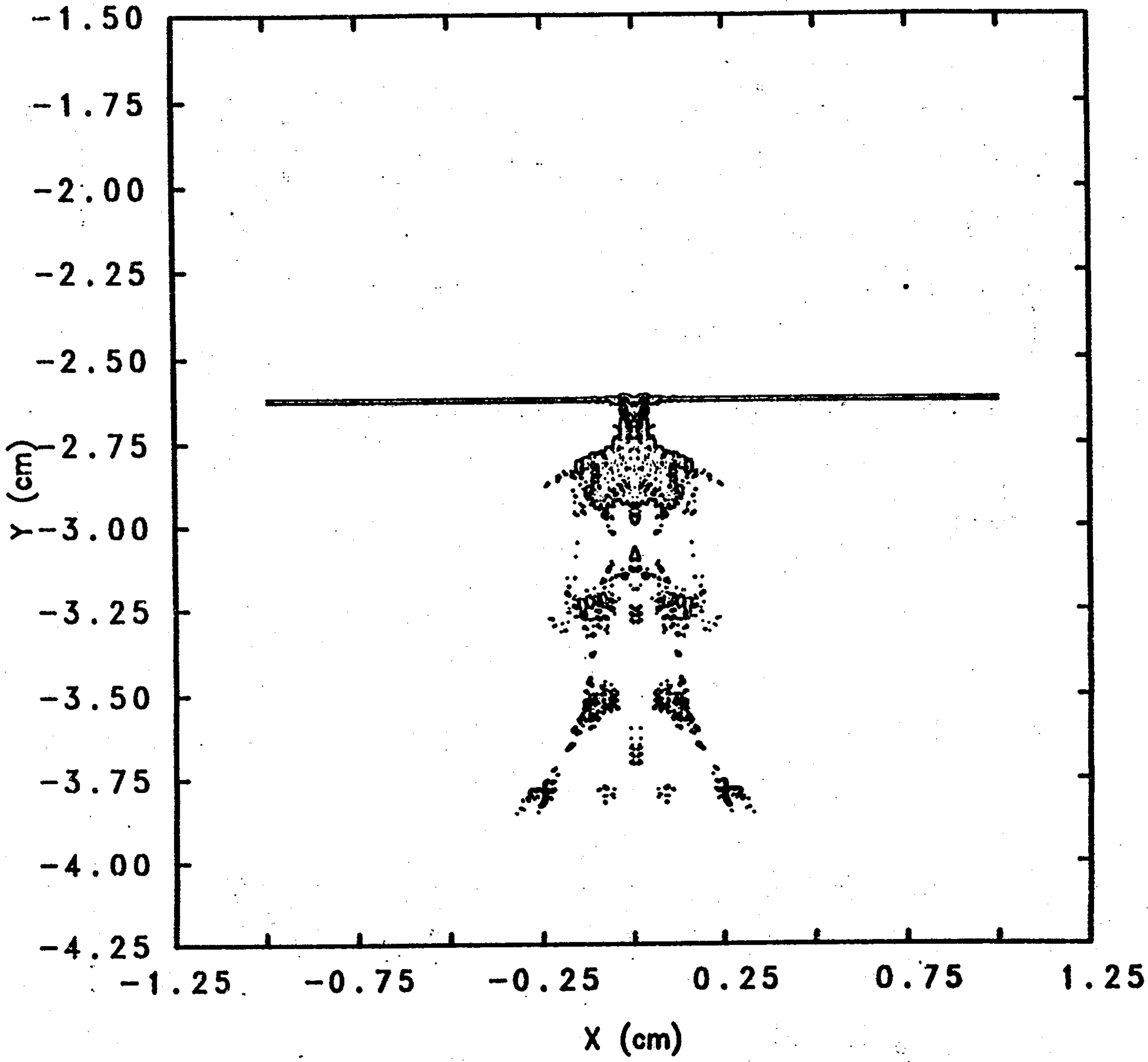
1.200E+01


-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

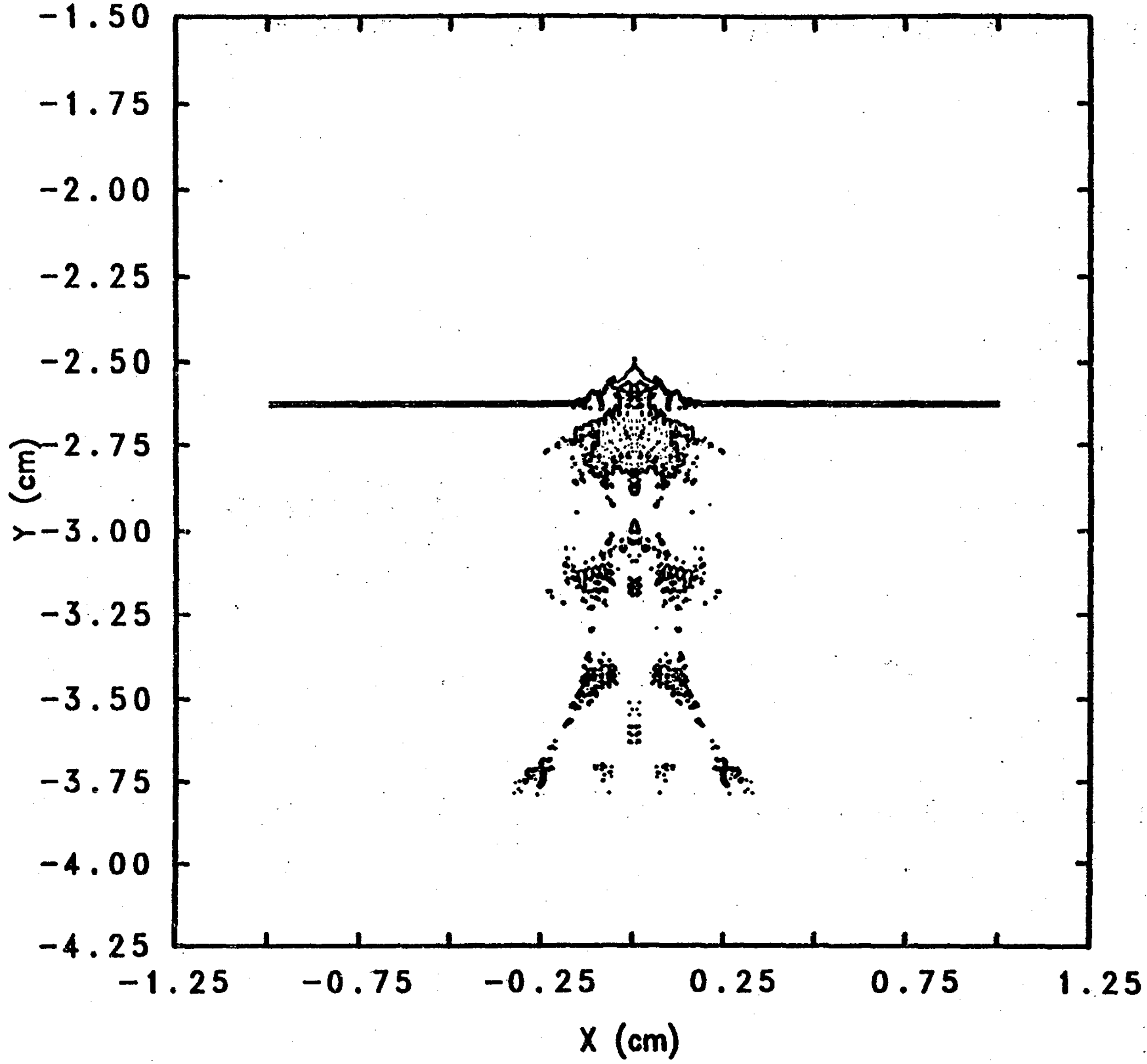
t = 12.61 μsec


-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 12.81 μsec

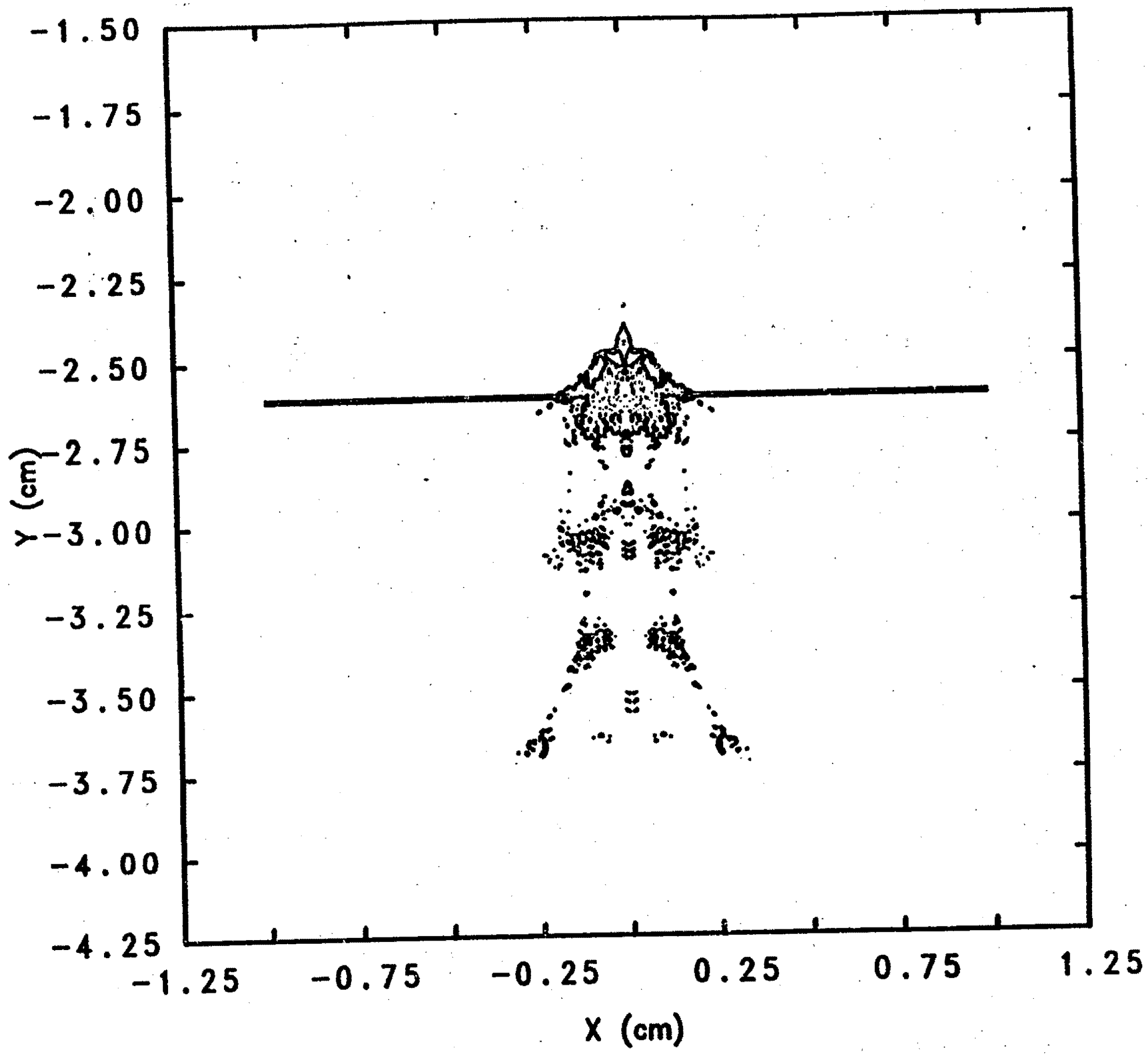

-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 13.01 μsec

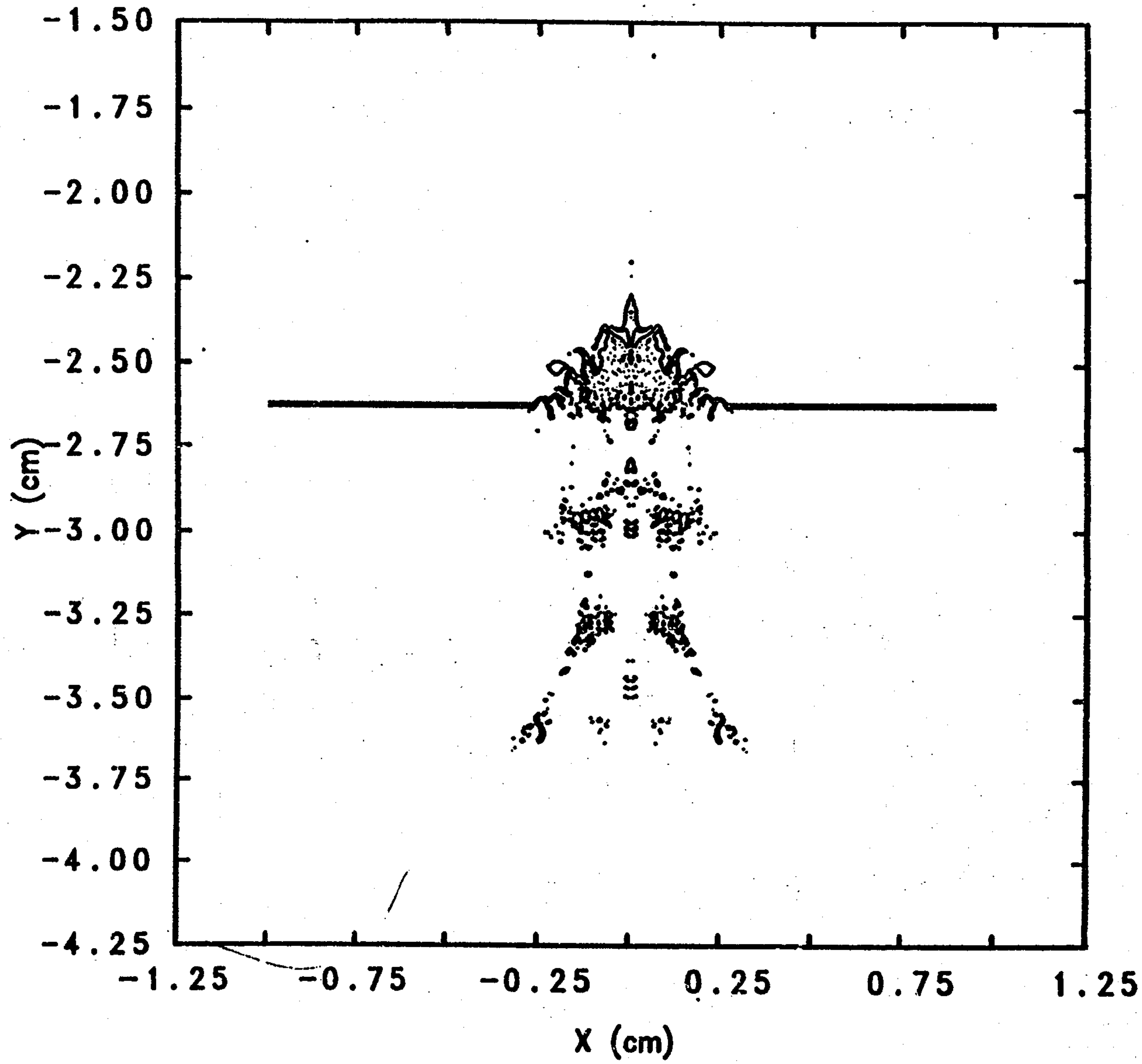


-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

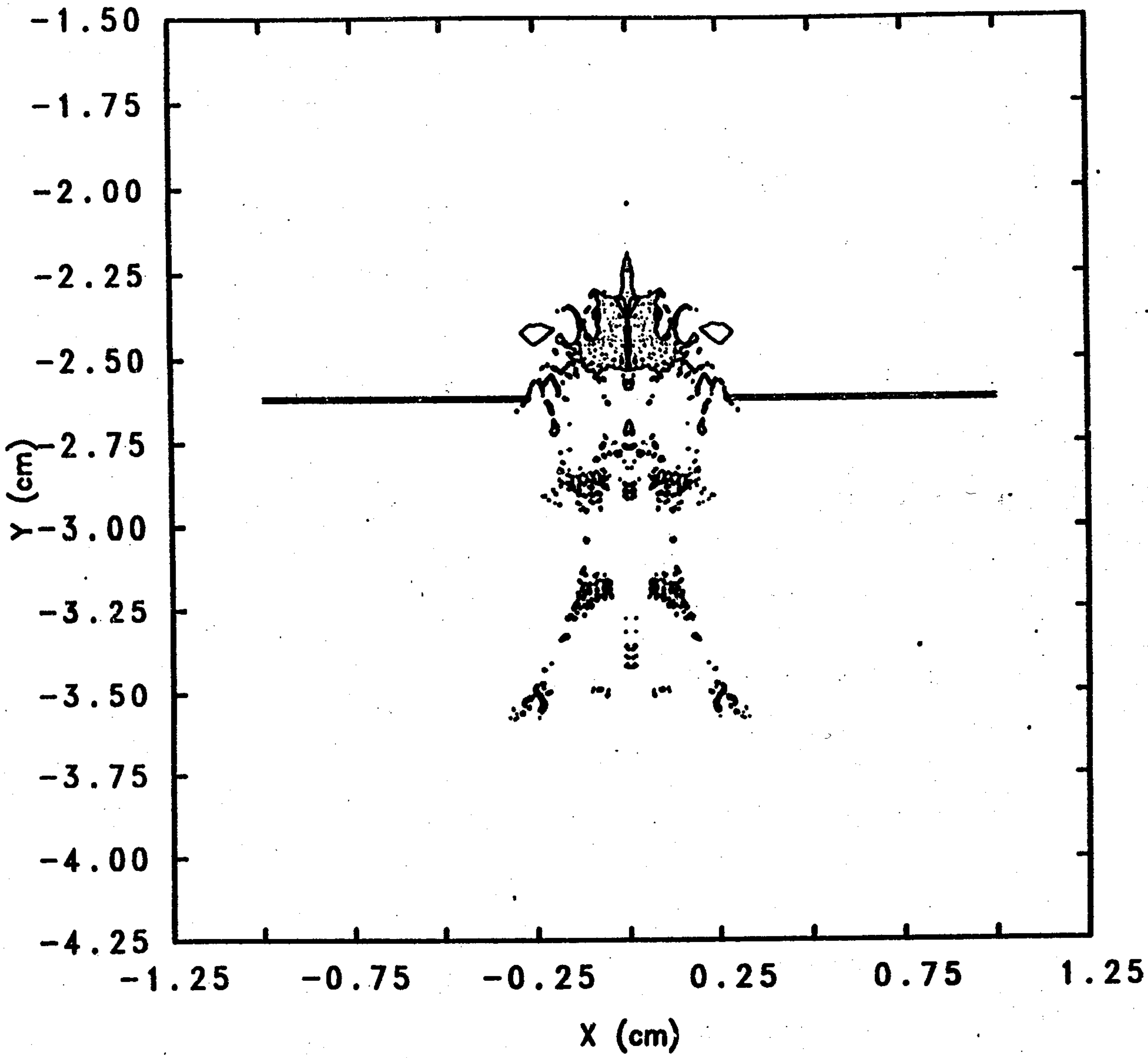
t = 13.21 μsec


-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

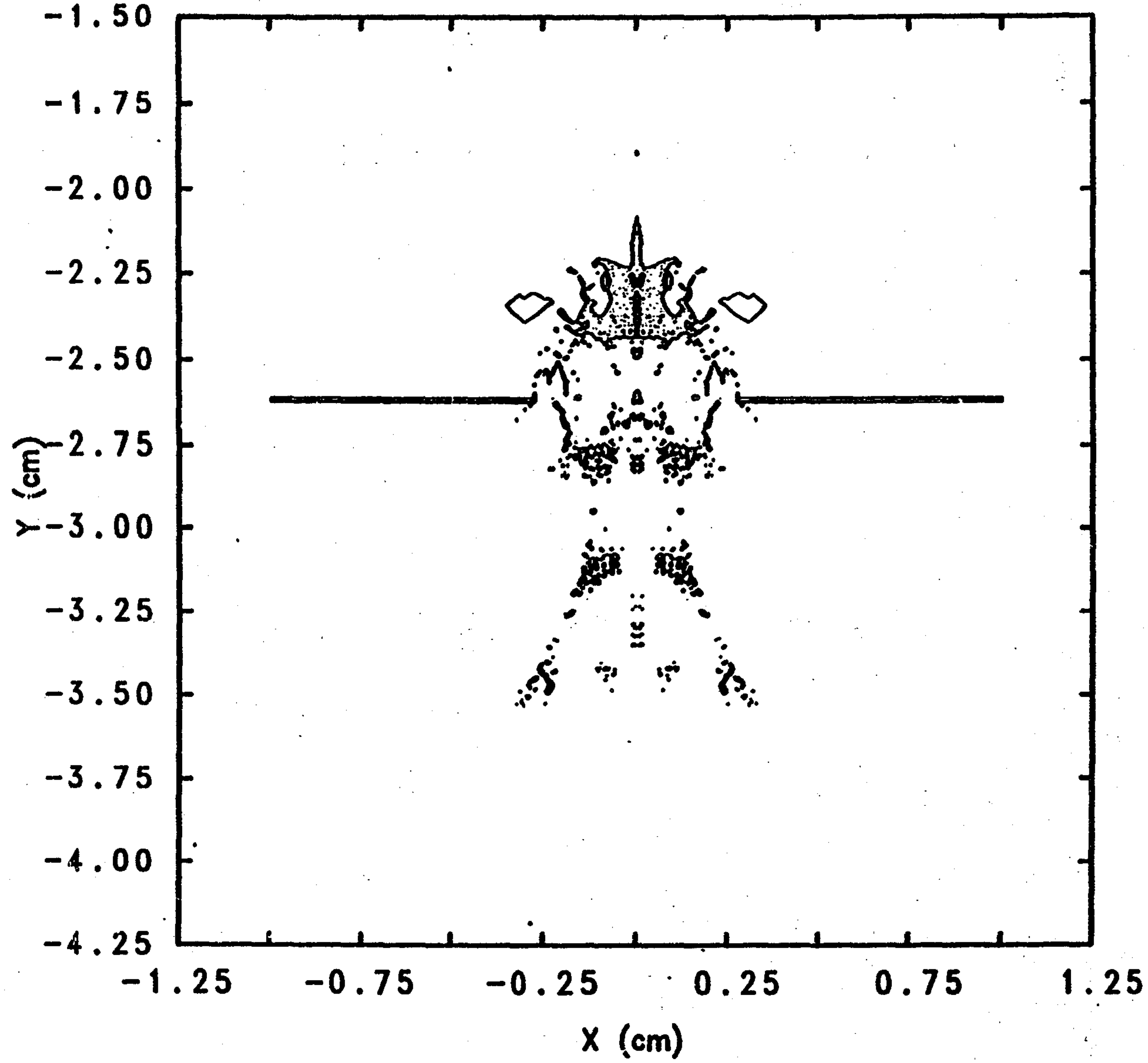
t = 13.41 µsec


-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

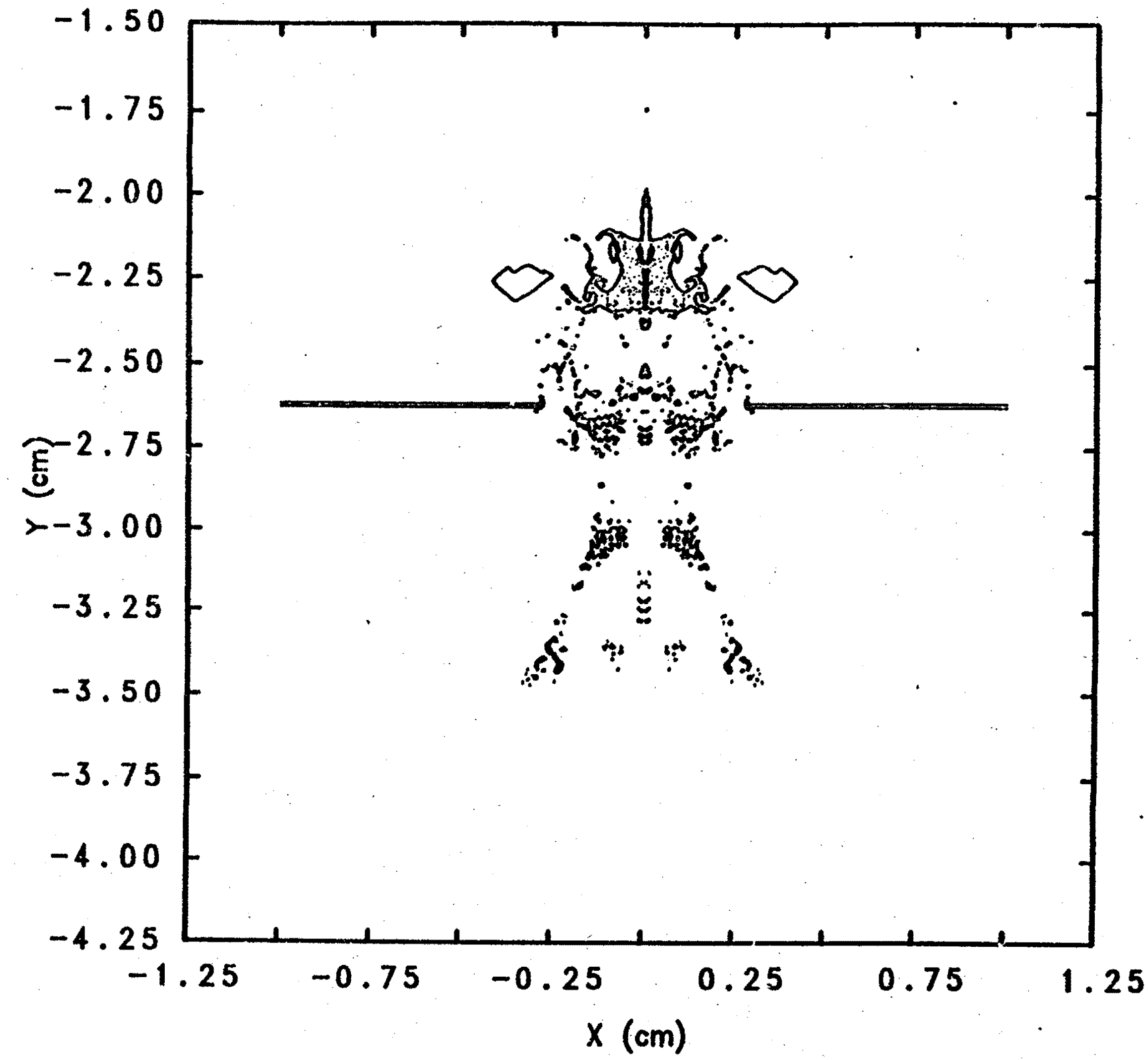
t = 13.61 μsec


Y (cm)
-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 13.81 µsec


-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

t = 14.01 µsec

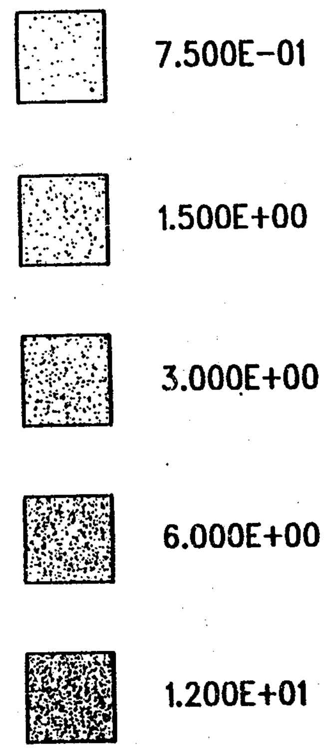

-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
-4.25
Y (cm)
-1.25
-0.75
-0.25
0.25
0.75
1.25
X (cm)

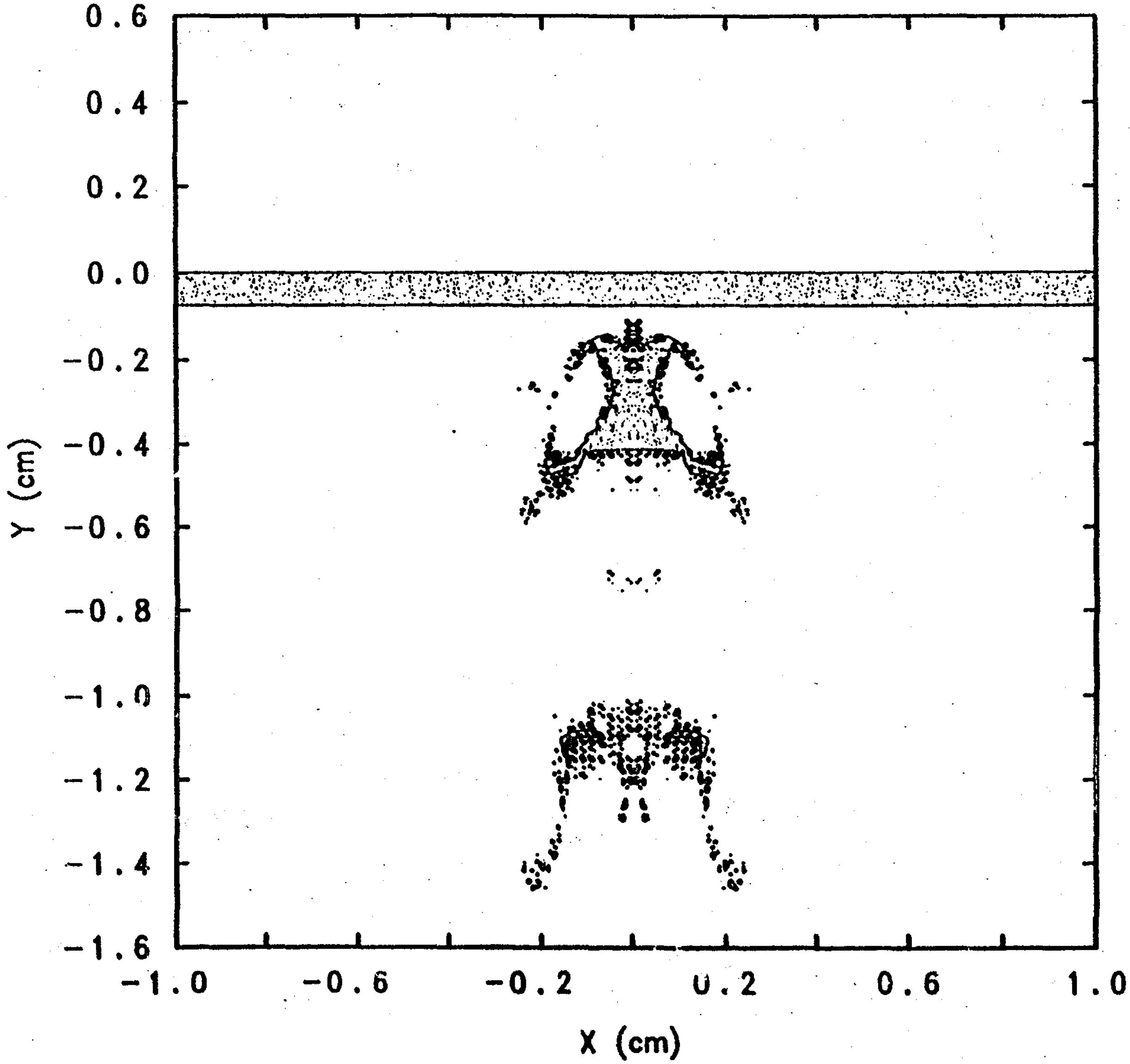
t = 14.21 μsec

APPENDIX F

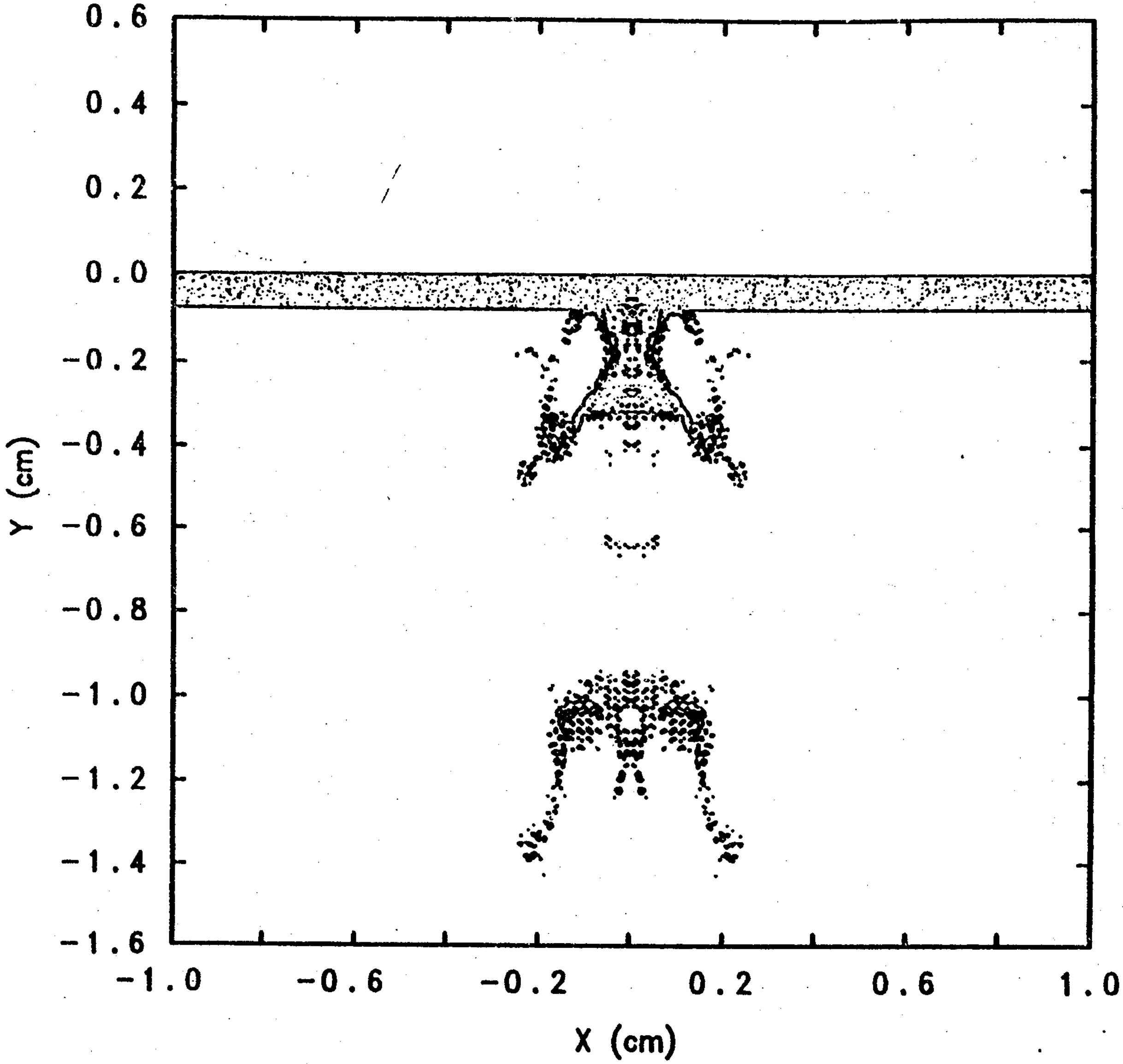
Legend

Density (g/cm³)



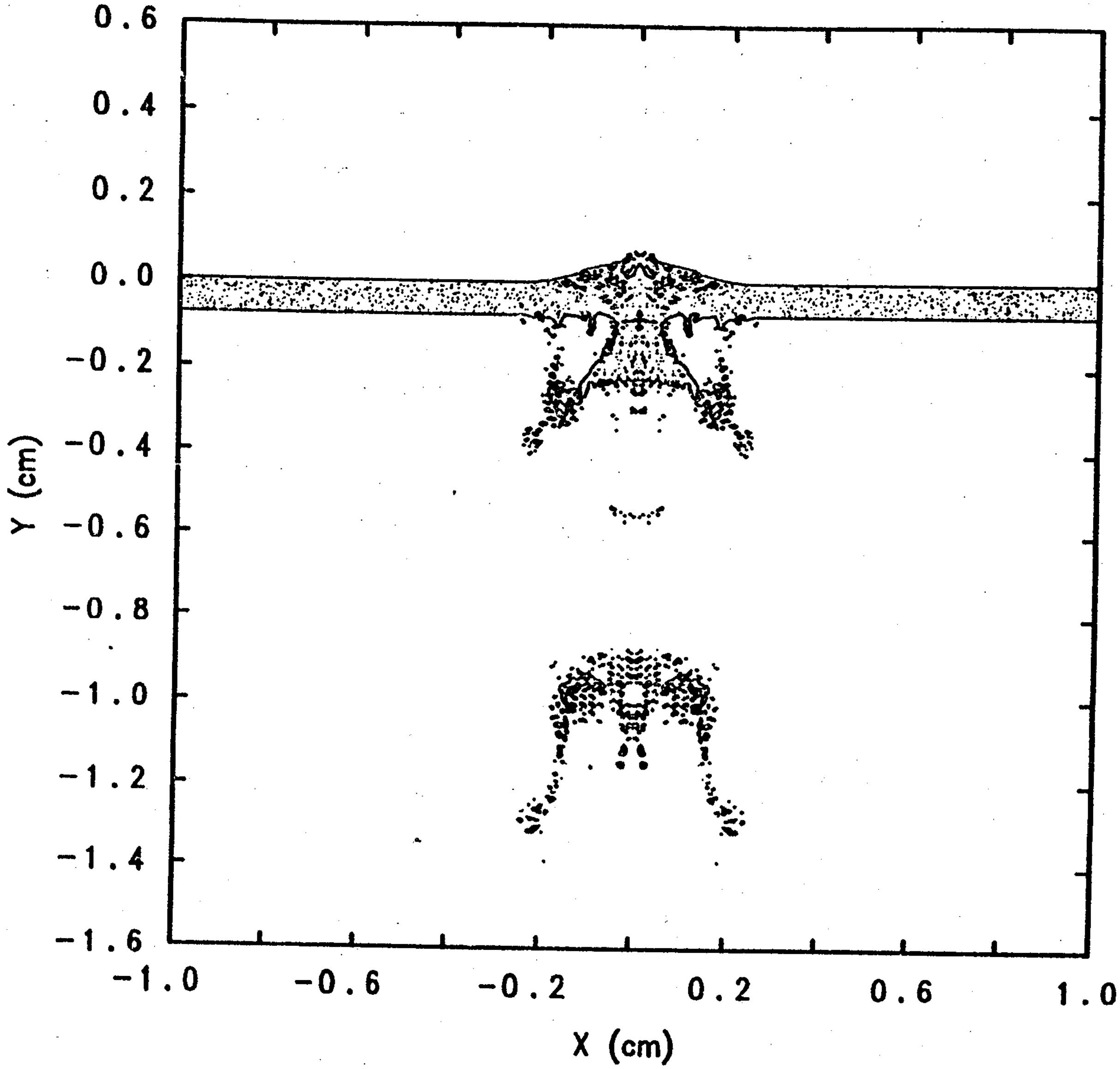


t = 18.11 μsec

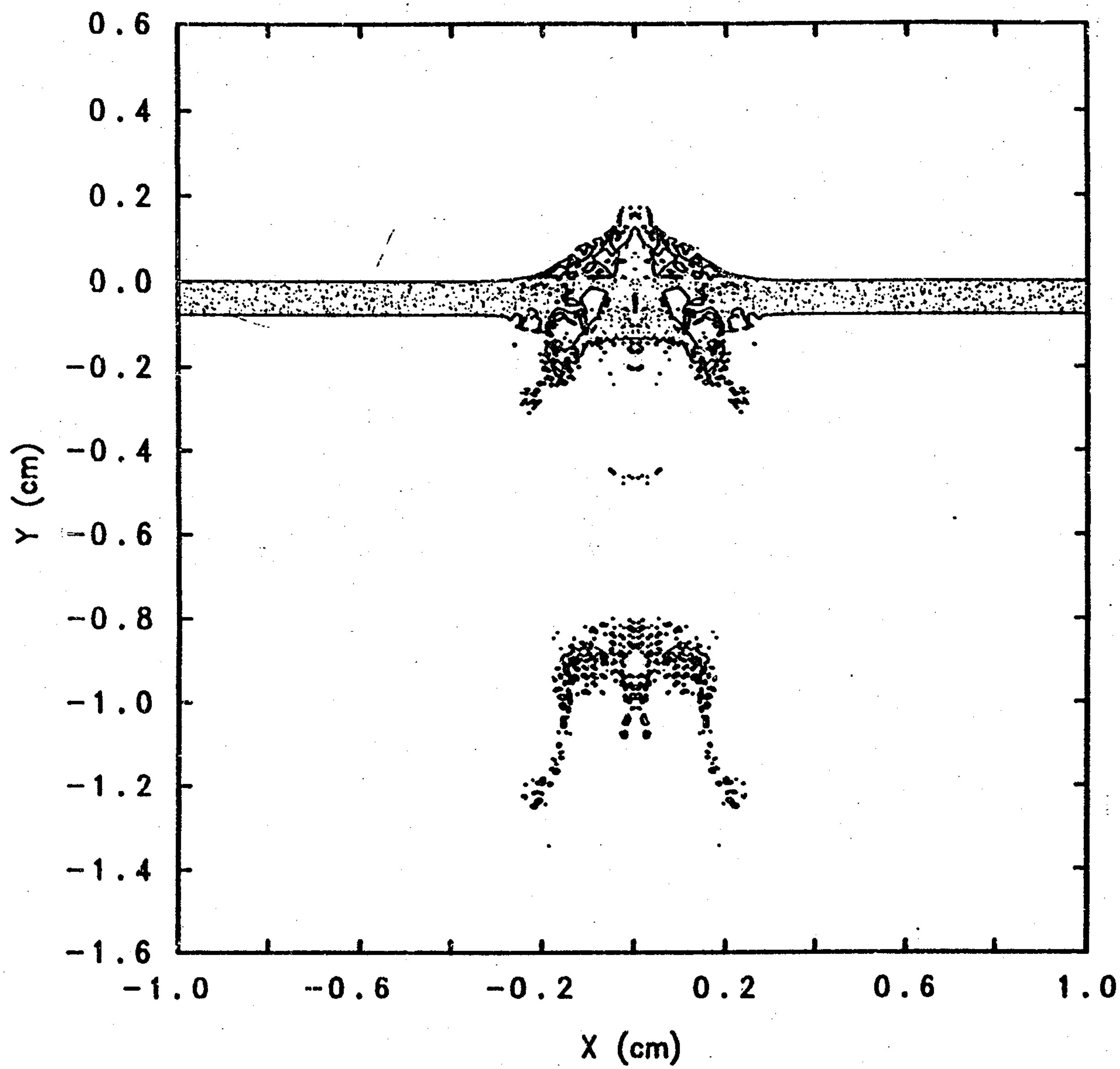


t = 18.31 μsec

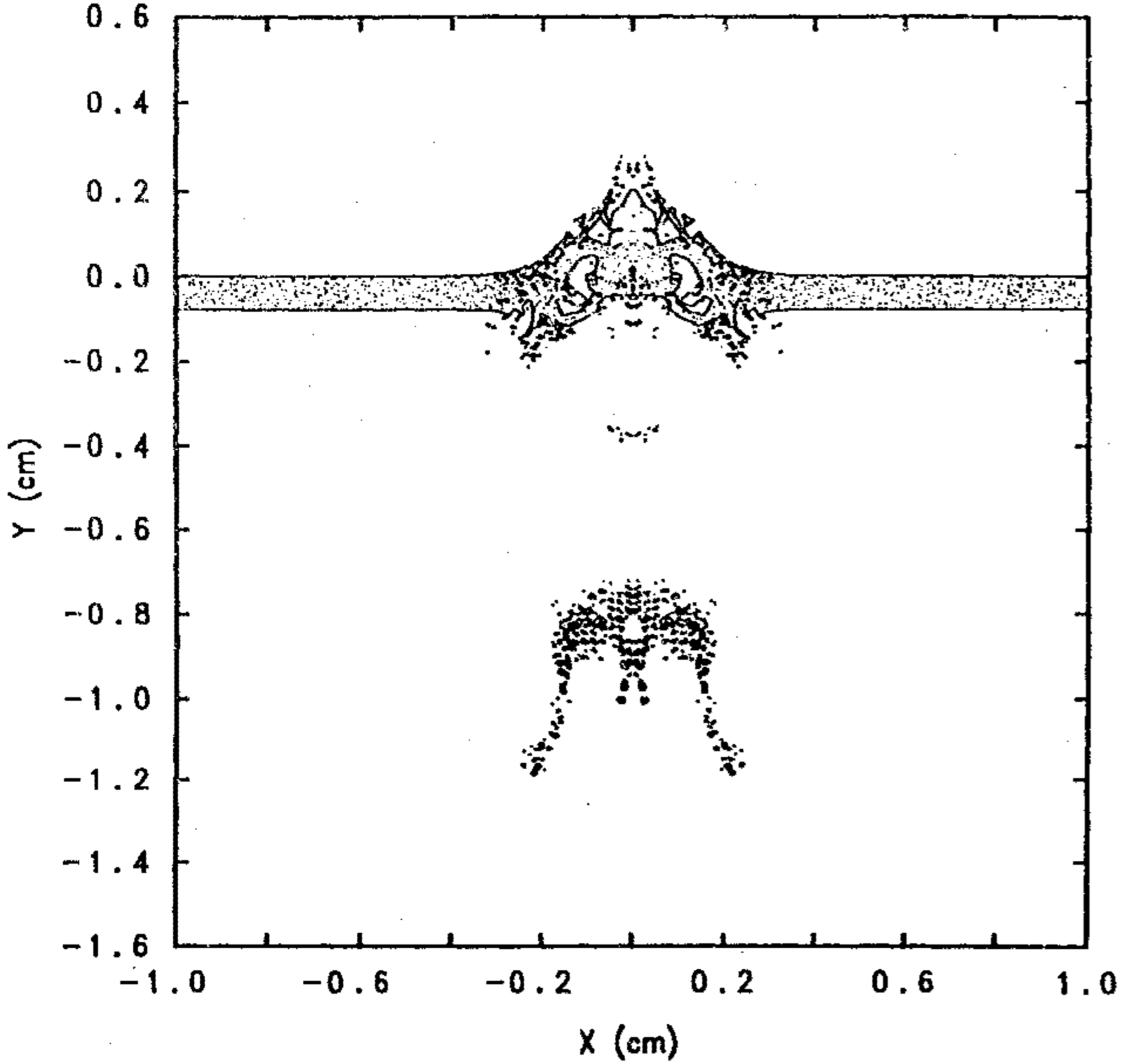
F-4



t = 18.51 µsec

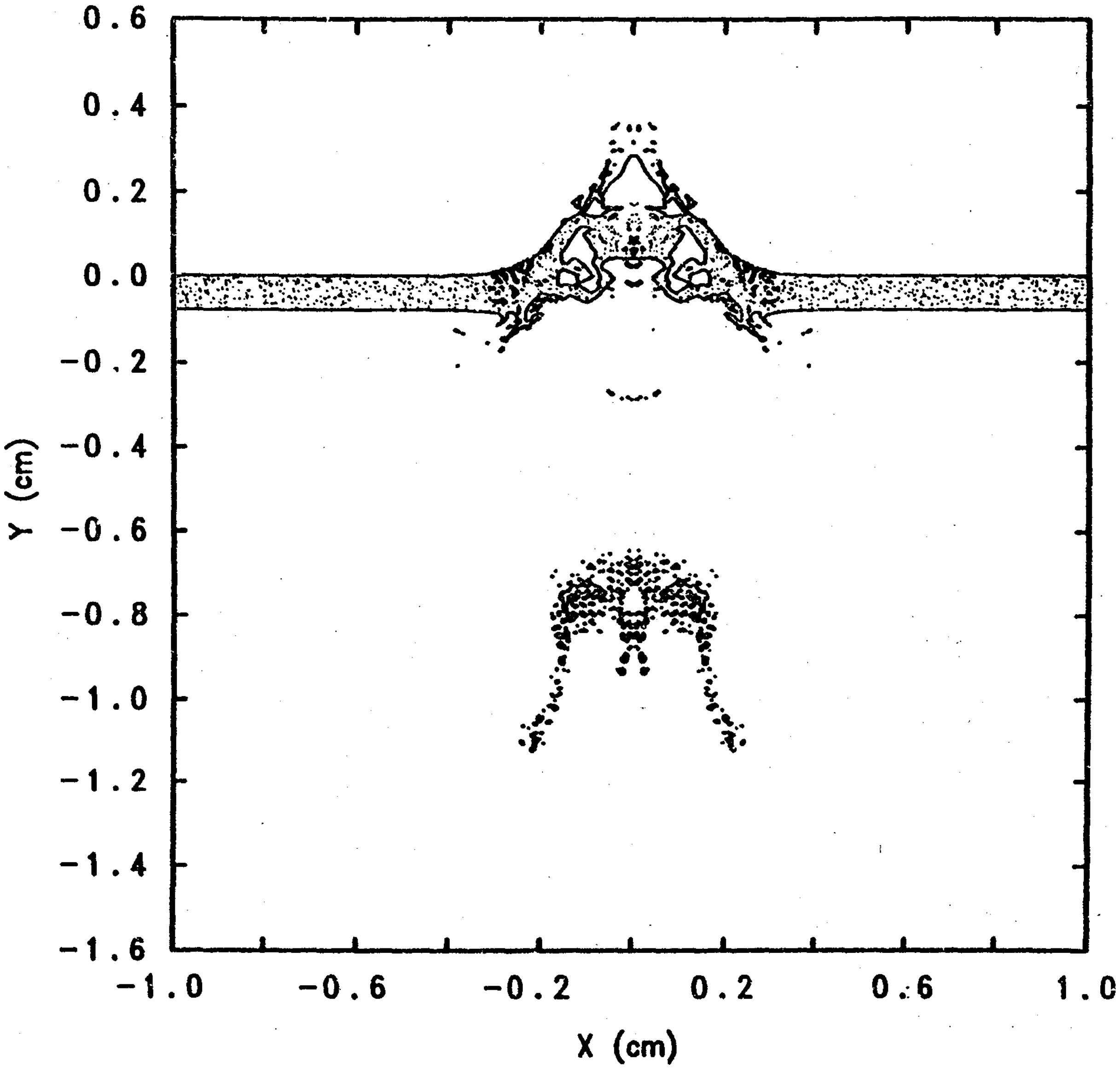


t = 18.71 μsec



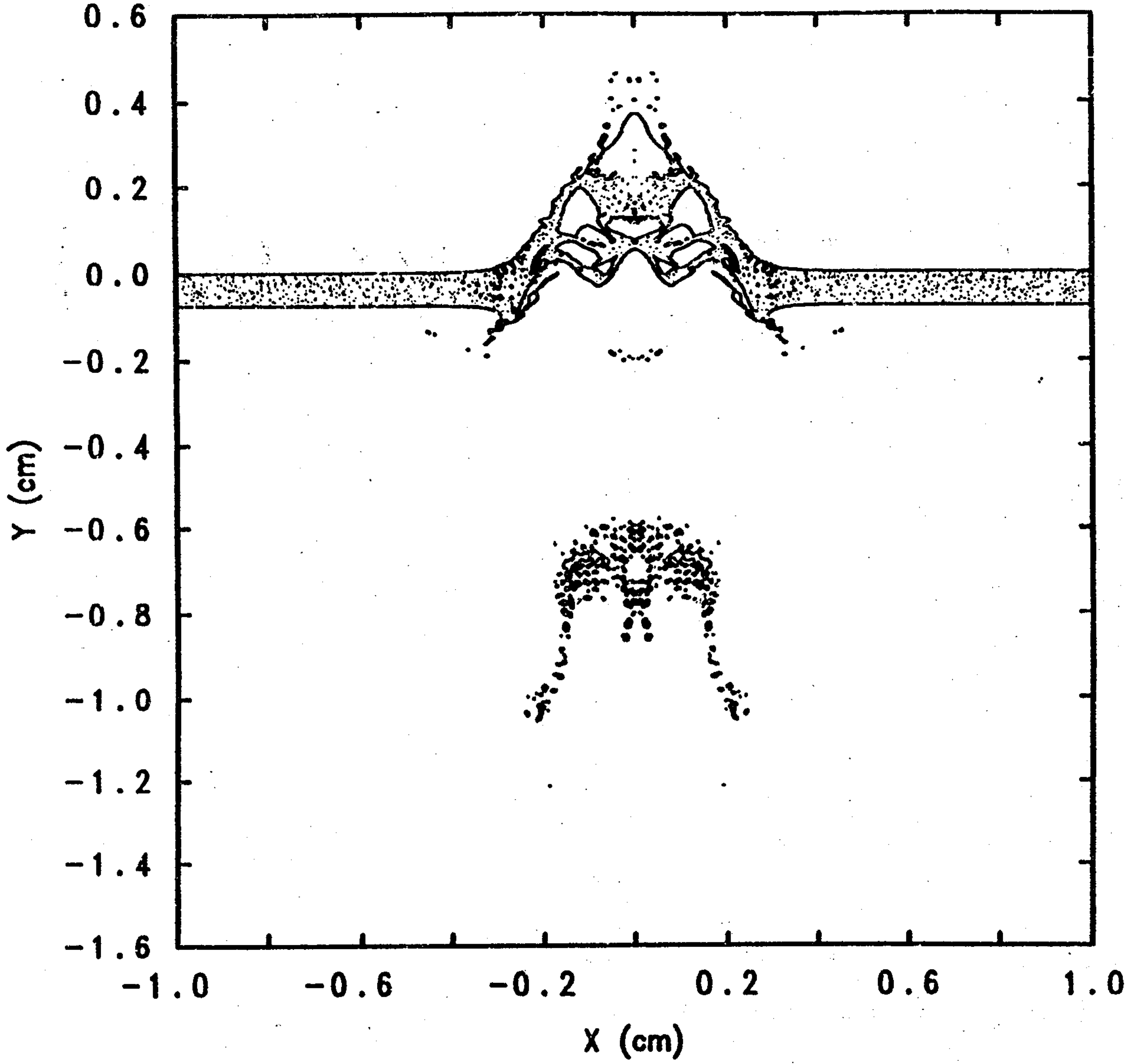
t = 18.91 μsec

F-7

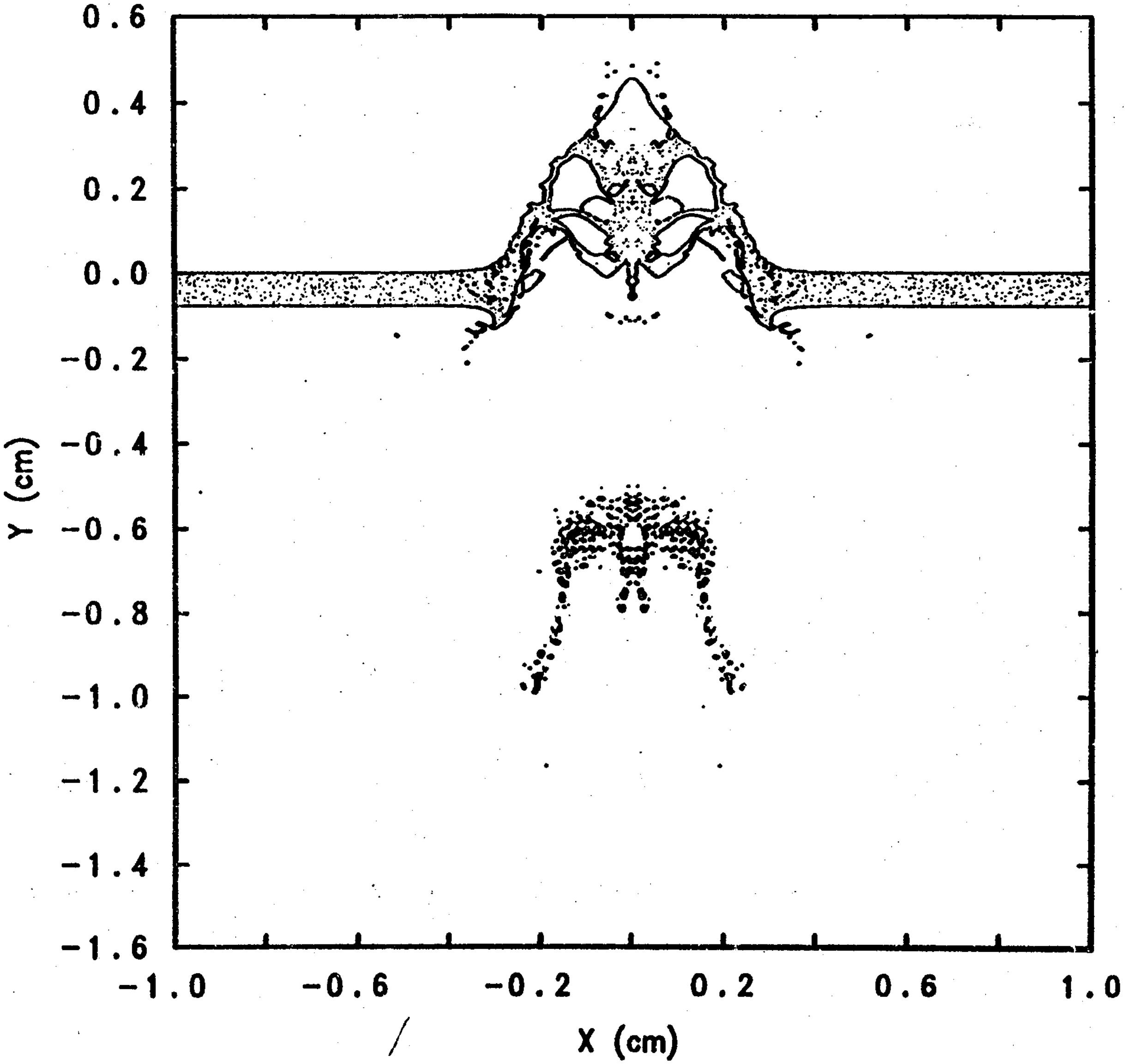


t = 19.11 μsec

F-8

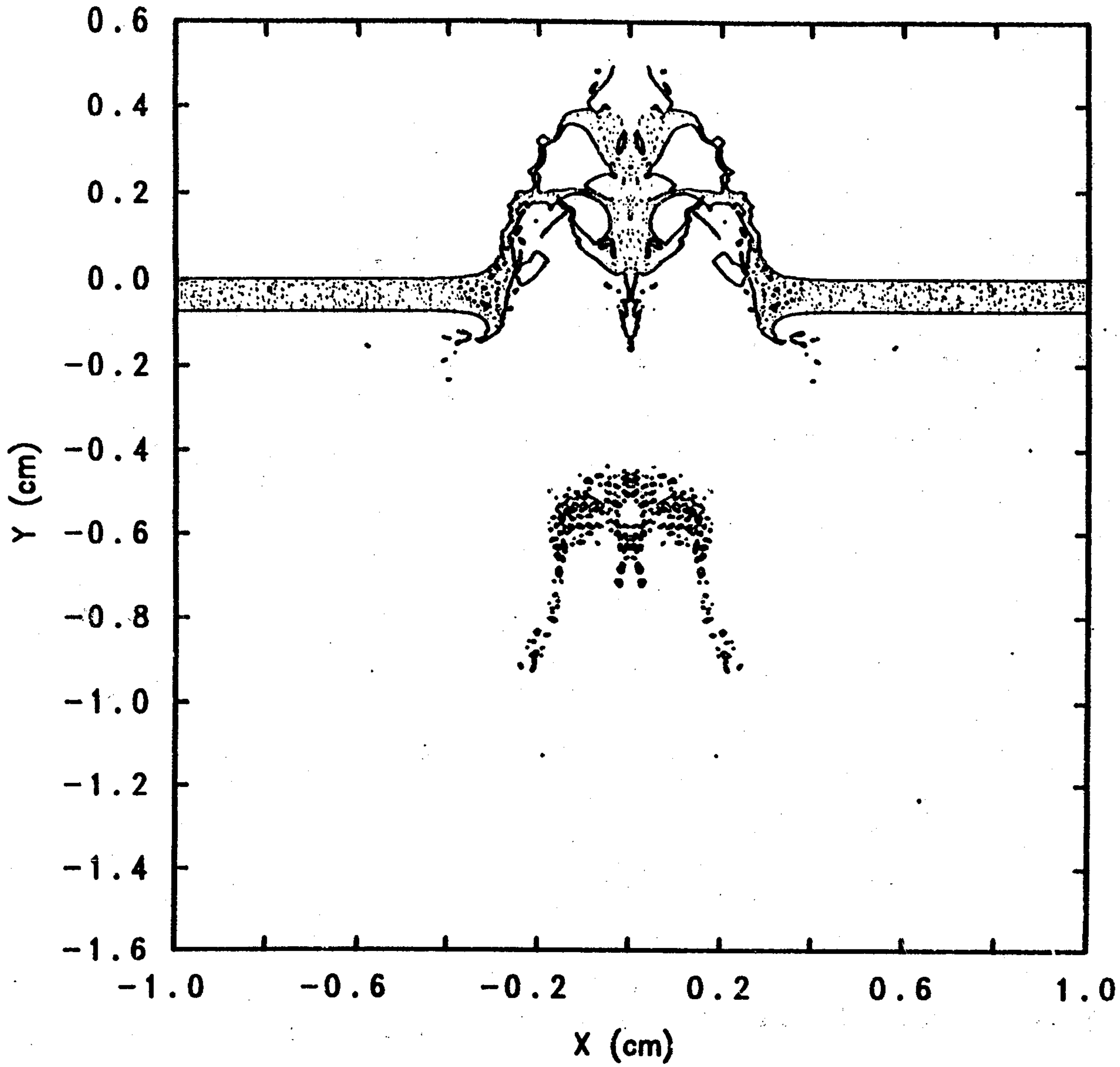


t = 19.31 μsec

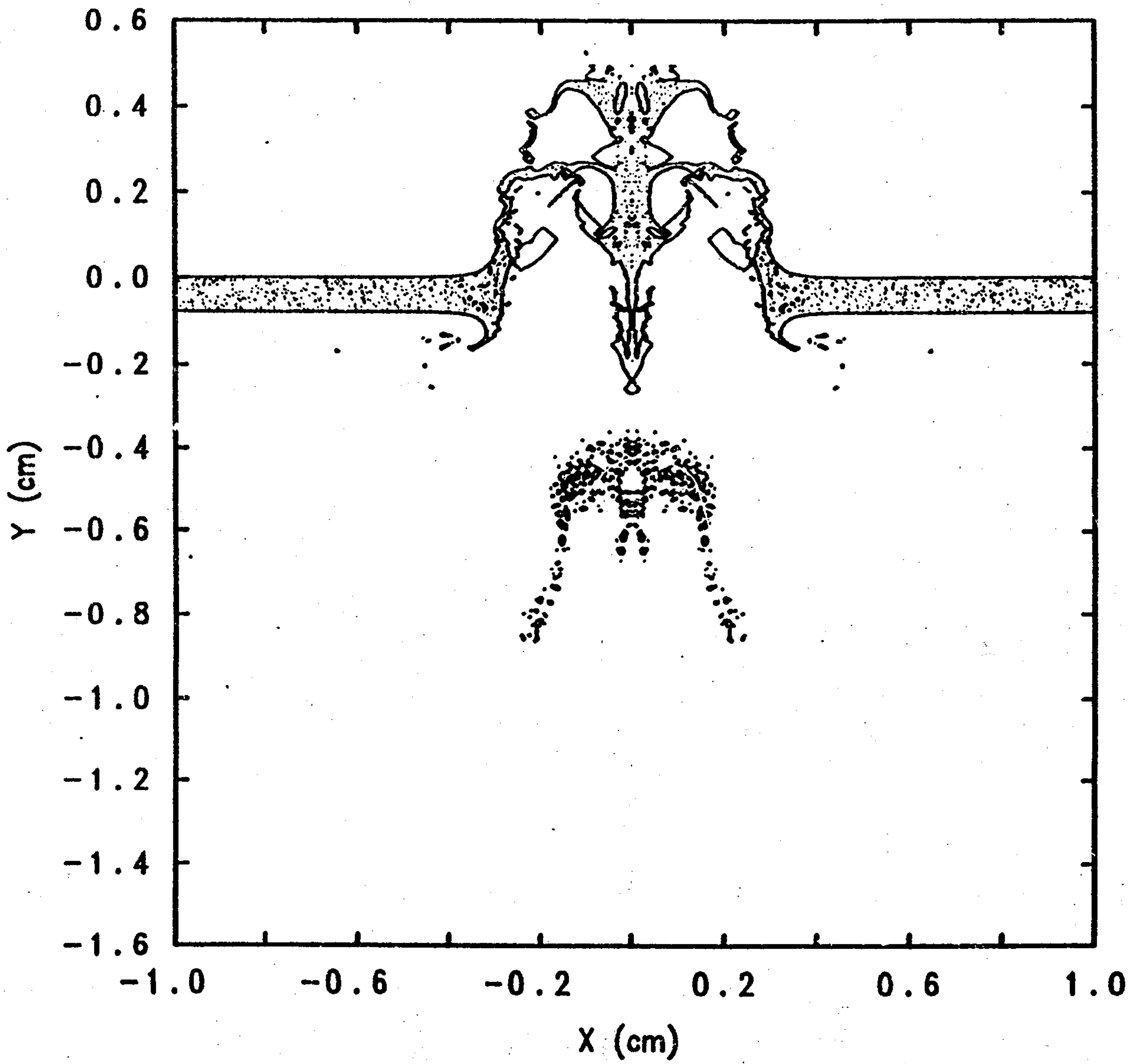


t = 19.51 μsec

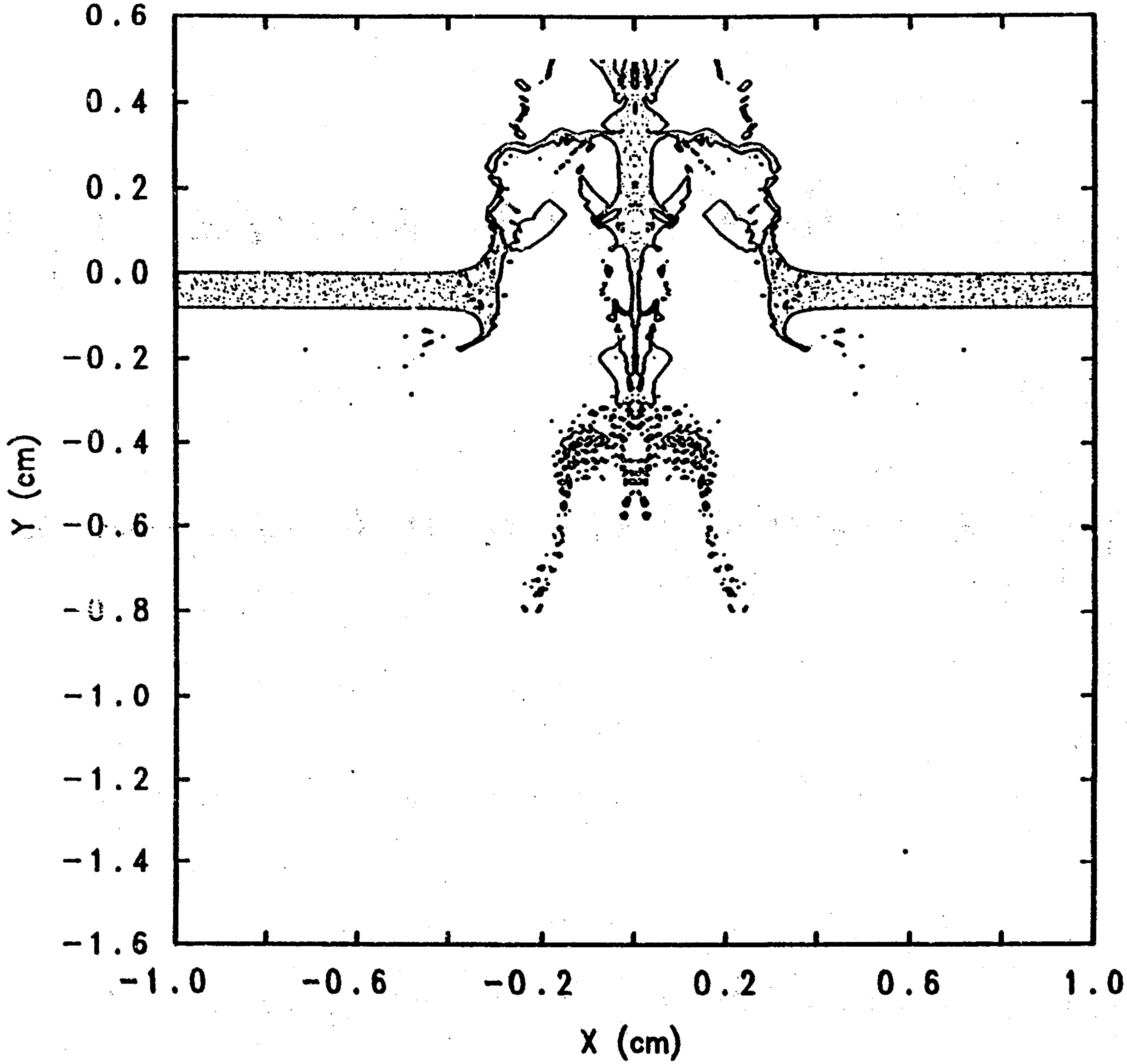
F-10



t = 19.71 μsec



t = 19.91 μsec



t = 20.11 μsec

END

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