UCRL-ID-144934

LLNL Modeling Calculations in Support of the NMD EOS Program: FY01 3Q Report

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July 1, 2001

U.S. Department of Energy

Lawrence
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Introduction

A program to examine equation-of-state (EOS) issues of interest to the National Missile Defense (NMD) program has been underway for a couple of years. There are current plans to conduct experiments at Sandia National Laboratory in Albuquerque. The initial experiments will be two-dimensional: a thin flyer will normally impact a target at two nominal velocities 6 km/s and 11 km/s. A witness plate is placed parallel to the target, separated from it by a 75 mm gap. Several channels of VISAR measure the particle velocity at different locations at the rear of the witness plate. A schematic of the experimental configuration is shown in Figure 1.

At a kick-off meeting in March 2001, the initial computational task for all three laboratories (SNLA, LANL, and LLNL) was to calculate the witness plate particle velocity profiles produced by the two contemplated projectile sizes at both projectile velocities. This report documents these calculations as well as further calculations prompted by the initial results.

First Series of Modeling Calculations

Calculations setup

Modeling calculations are done with the CALE code, which is a 2-D axisymmetric hydrodynamics code with arbitrary Lagrange Eulerian capabilities. In these calculations, there is an axis of rotational symmetry located at zero in the radial direction. Physically, zones are hoops whose axis is this rotational symmetry axis. Many figures in this report are cross sections with the rotational symmetry axis running left to right. The radial coordinate (r) is up down, the axial coordinate z is left right. The calculation setup for a 12.7 mm diameter projectile is shown in Figure 2. The rotational symmetry axis is at r=0 and zoning is indicated in the upper half. The projectile, target and witness plate appear as rectangles, but this is a cross section so they are physically thin cylinders. Zoning is difficult to see for the projectile, target and witness plate, it is better visible in the close-ups shown in Figures 3 and 4. The calculational setup and close up for a 17 mm diameter projectile are shown in Figures 5 and 6. Tracer points that move with the material are located at the rear of the witness plate on axis and at 2 mm intervals radially.

Standard zoning is 140x113 zones along the axis and radius, respectively. This amounts to 9 zones across the thickness of the projectile 10 zones across the thickness of the target and the witness plate, the target and the witness plate as well as 100 zones across the 75 mm gap between the target and the witness plate. Radially zoning is close to uniform with 9 zones across the 6.35 mm radius projectile and 12 across the 8.5 mm radius one.

The background material is vacuum with a density of 10^{-6} g/cm^3. The projectile EOS is a Gruneisen one with coefficients determined for TI6Al4V which is the titanium alloy the projectile is made of. The target EOS is a tabular one, referred to as LEOS at LLNL, which treats all phases of materials. The EOS treats the heterogeneous silicate phenolic as a homogeneous material. The witness plate EOS is a polynominal one with coefficients determined for the 6061-T6 aluminum alloy. All material constitutive models are elastic plastic. Material failure (zero strength) takes place when the tensile strength is exceeded in tension or when the accumulated effective plastic strain exceeds the maximum specified in the constitutive model. Material parameters are listed in Table 1.

Table 1
Material Parameters

Projectile:	Gruneisen EOS for Ti6Al4V alloy density = 4.419 g/cm^3 coefficients c=0.513, S1=1.028, S2=0, S3=0, G0=1.23, A=0.17 modulus = 419 kbars, yield strength = 13.2 kbars maximum effective plastic strain = 2 tensile strength = 25 kbars
Target:	LEOS for silicate phenolic (LEOS 7020) density = 1.644 g/cm^3 modulus = 232 kbars, yield strength = 2 kbars no effective plastic strain based failure tensile strength = 2 kbars
Witness plate:	polynomial EOS for 6061 T6 aluminum alloy density = 2.703 g/cm^3 coefficients A0=0, Al=0.742179, A2=0.604876, A3=0.187029, B0=1.97, B1=0.48, B3=0 modulus = 276 kbars, yield strength = 2.9 kbars maximum effective plastic strain = 0.5 tensile strength = 12 kbars

Results of the Calculations

Results of the modeling calculations for a 12.7 mm diameter projectile at 6 km/s initial velocity are shown in Figures 7 and 8. Figure 7 is a materials map at the end of the calculation with zoning indicated above the symmetry axis. The particle velocity profiles, at the rear of the witness plate, on axis and 2, 4, and 6 mm away are shown in Figure 8. Analogous results for a 17 mm diameter projectile are shown in Figures 9 and 10. Analogous results for an initial projectile velocity of 11 km/s are shown in Figures 11 through 14.

Second Series of Modeling Calculations

To increase the meaningful length of the particle velocity record, we back the witness plate with a 10 mm thick LiF window. It is well known that the shock impedance of LiF is nearly identical to that of aluminum. We also restrict our attention to 17 mm diameter projectiles. Finally, we examine the effect of target strength and zoning on the calculated particle velocity profiles.

The model setup and close-ups with zoning are shown in Figures 15 through 17. Results for 6 km/s initial projectile velocity are shown in Figures 18 and 19, and Figures 20 and 21 for 11 km/s initial projectile velocity.

We investigate the effect of target strength by running calculations in which the yield strength of the target is doubled and halved. The results are shown in Figures 22 through 25 for 6 km/s initial projectile velocity. The calculated profiles, near axis, are shown in Figure 26. It is clear that the target yield strength strongly affects the calculated particle velocity profiles, both in amplitude and timing. Analogous results for an initial projectile velocity of 11 km/s are shown in Figures 27 through 31. At this higher velocity, the target strength has an even more dramatic effect on the calculated particle velocity peak amplitude.

Finally, we examine the effect of resolution by increasing zoning from 150x113 in the standard calculations with LiF backing to 240x225 zones. We keep the same number of zones across the thickness of the projectile target, witness plate and backing, but increase it by a factor of two across the gap and in the radial direction.

The model setup and close-ups with zoning are shown in Figures 32 through 34. Results for 6 km/s initial projectile velocity are shown in Figures 35 and 36. Analogous results for 11 km/s initial projectile velocity are shown in Figures 37 and 38. Comparison of the calculated particle velocity profiles with those obtained with standard zoning show little dependence on zoning. Direct comparisons of the particle velocity profiles on axis are shown in Figures 39 and 40.

Experimental Approach - I

- "Simple" 2-D/1 experiments
  - 0.8 mm Ti plates at 6 and 11 km/s striking SiPh target; 12.7 and 17 mm diameter
  - SiPh samples 4 mm thick
  - Photographs of debris cloud
  - Multiple visar recording on witness plate
  - Witness Plate 4 mm thick
  - Stand off distance 75 mm

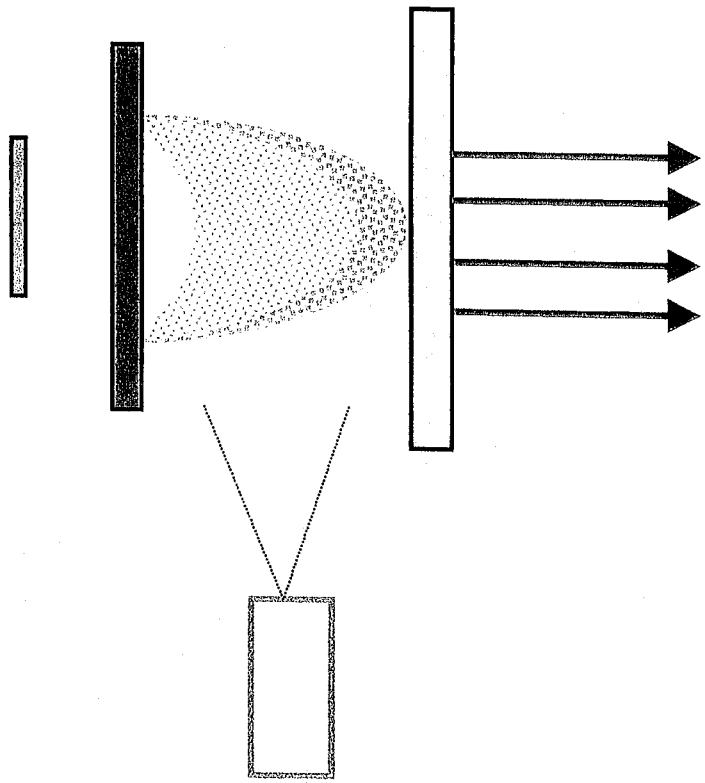
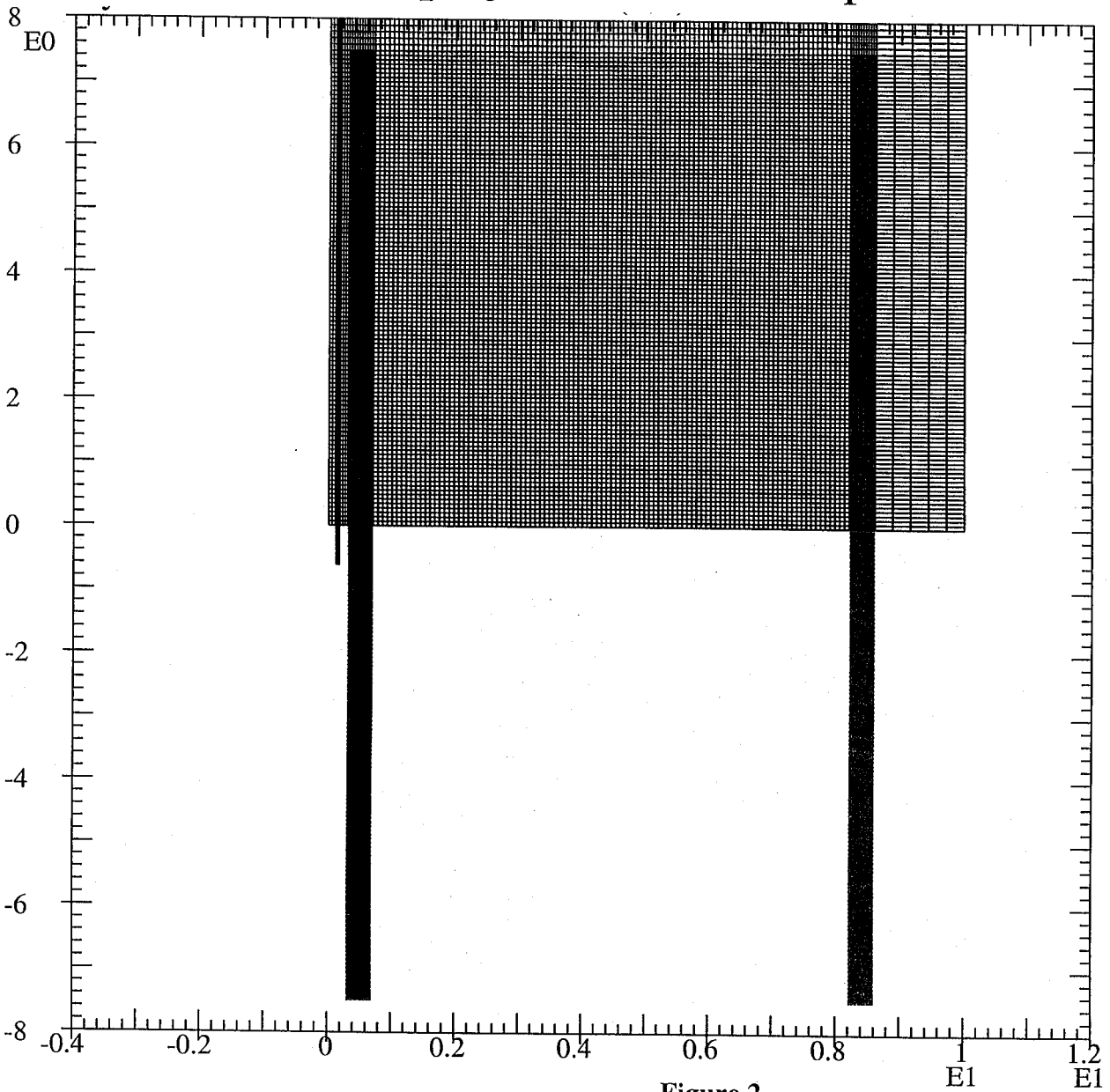


Figure 1

First series NMD EOS experiments modeling calculations

12.7mm diameter projectile: materials plot and zoning



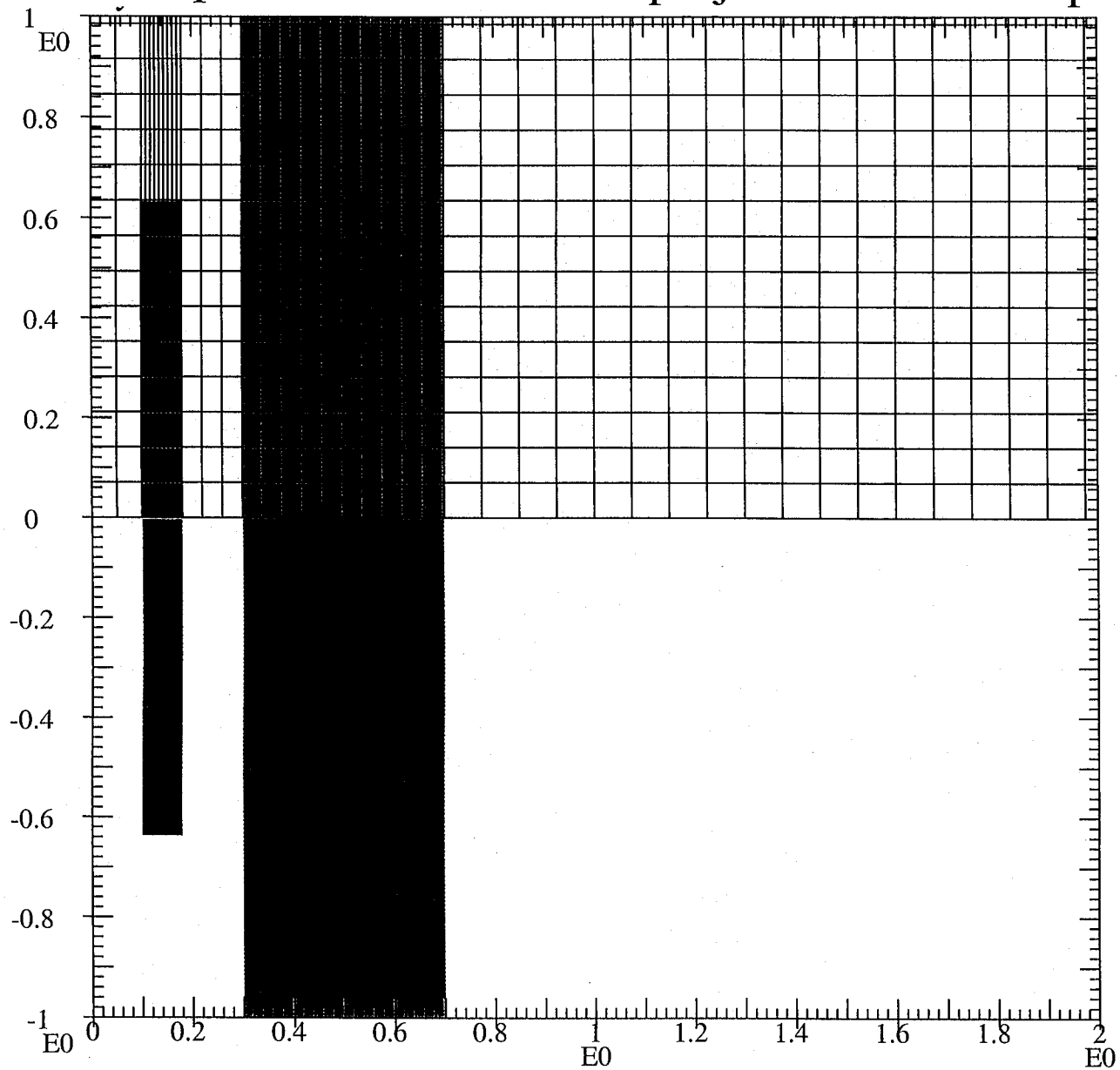
Red: projectile
Green: target
Blue: witness plate
Yellow: vacuum background

Figure 2

nmda-1-mg-6-18-2001

First series NMD EOS experiments modeling calculations

Closeup of12.7mm diameter projectile: materials plot and zoning



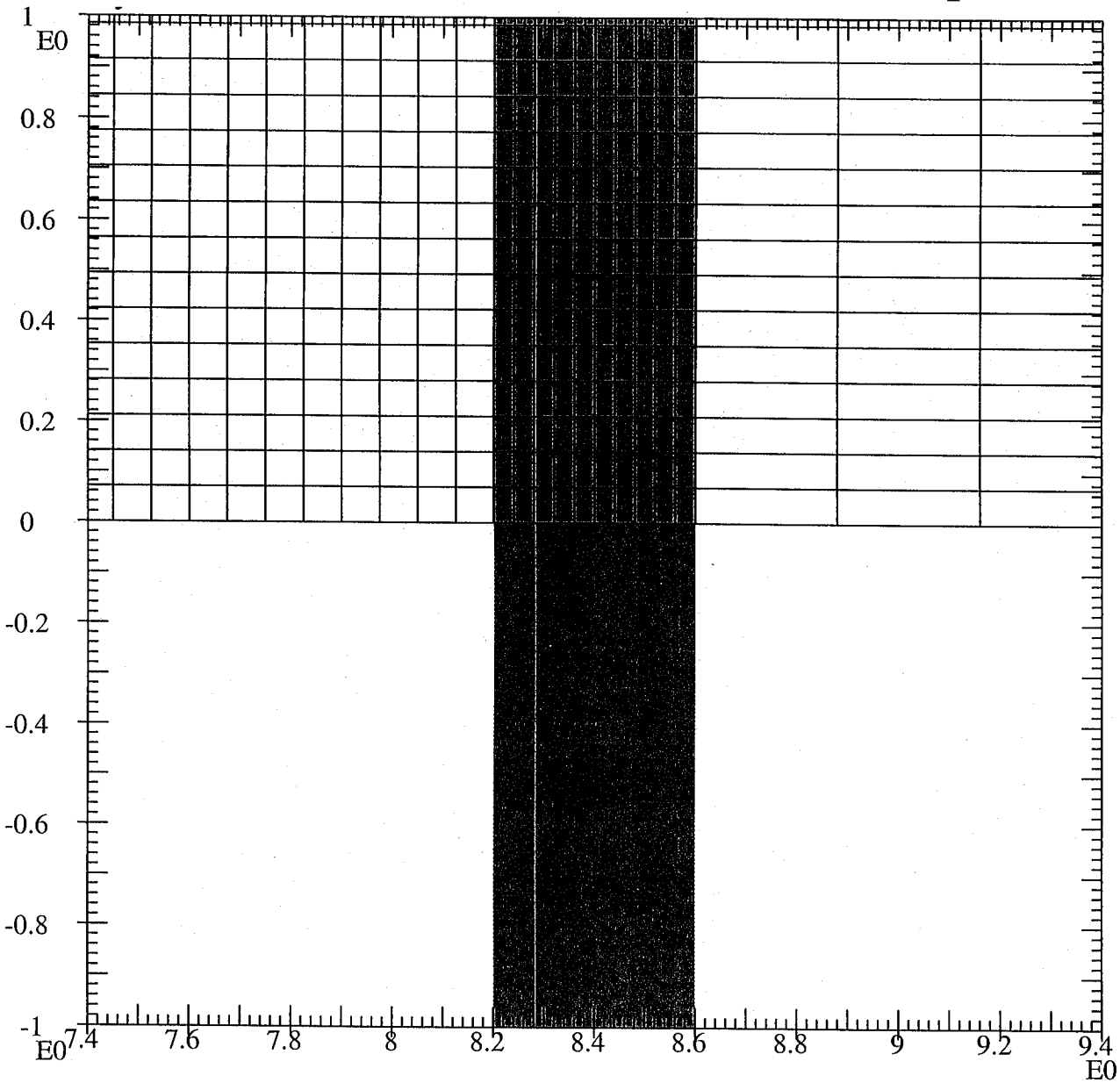
Red: projectile
Green: target
Yellow: vacuum background

nmda-2-mg-6-18-2001

Figure 3

First series NMD EOS experiments modeling calculations

Closeup of witness plate and gap: materials plot and zoning



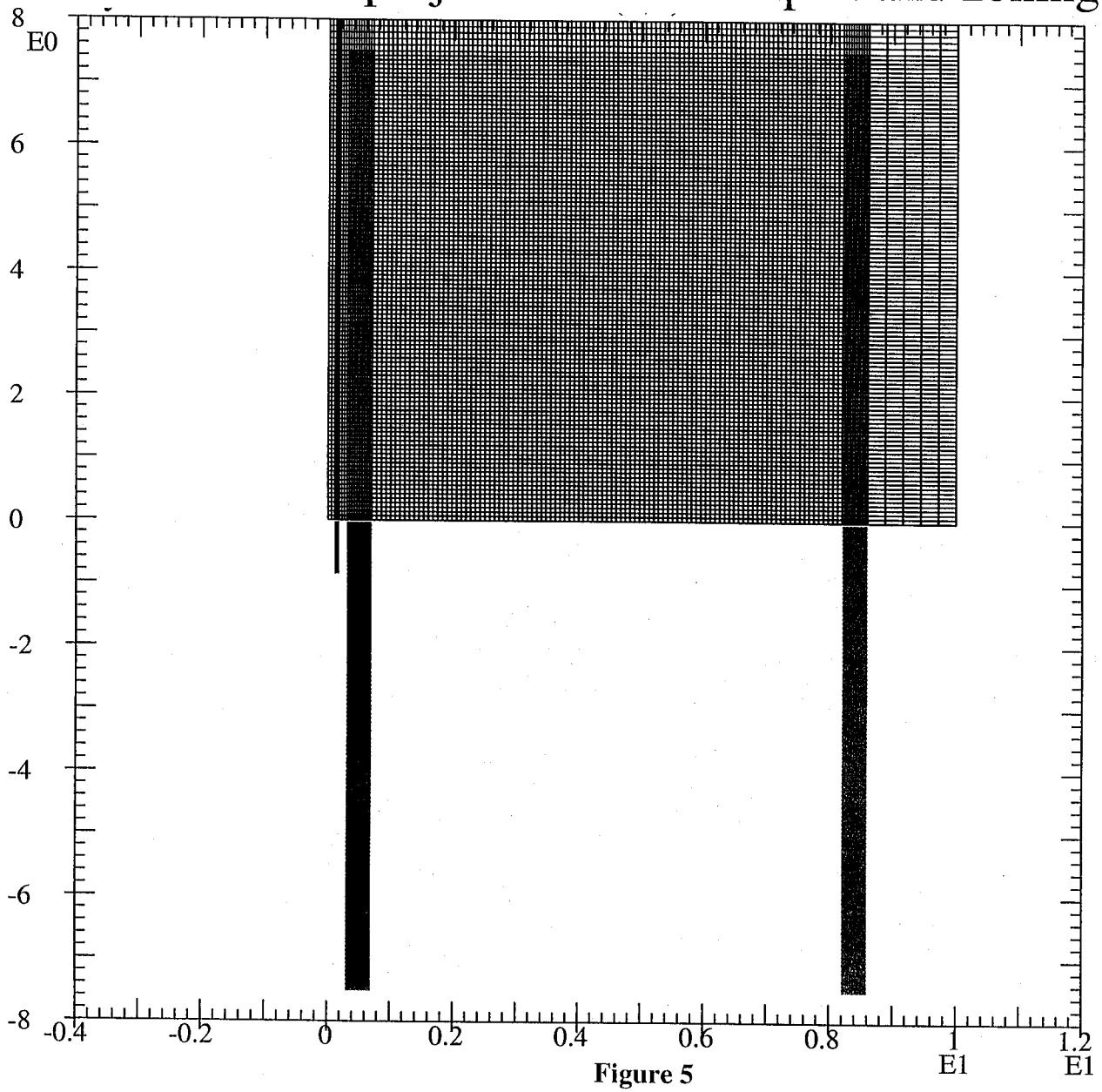
Blue: witness plate
Yellow: vacuum background

nmda-5-mg-6-18-2001

Figure 4

First series NMD EOS experiments modeling calculations

17mm diameter projectile: materials plot and zoning



Red: projectile
Green: target
Blue: witness plate
Yellow: vacuum background

Figure 5

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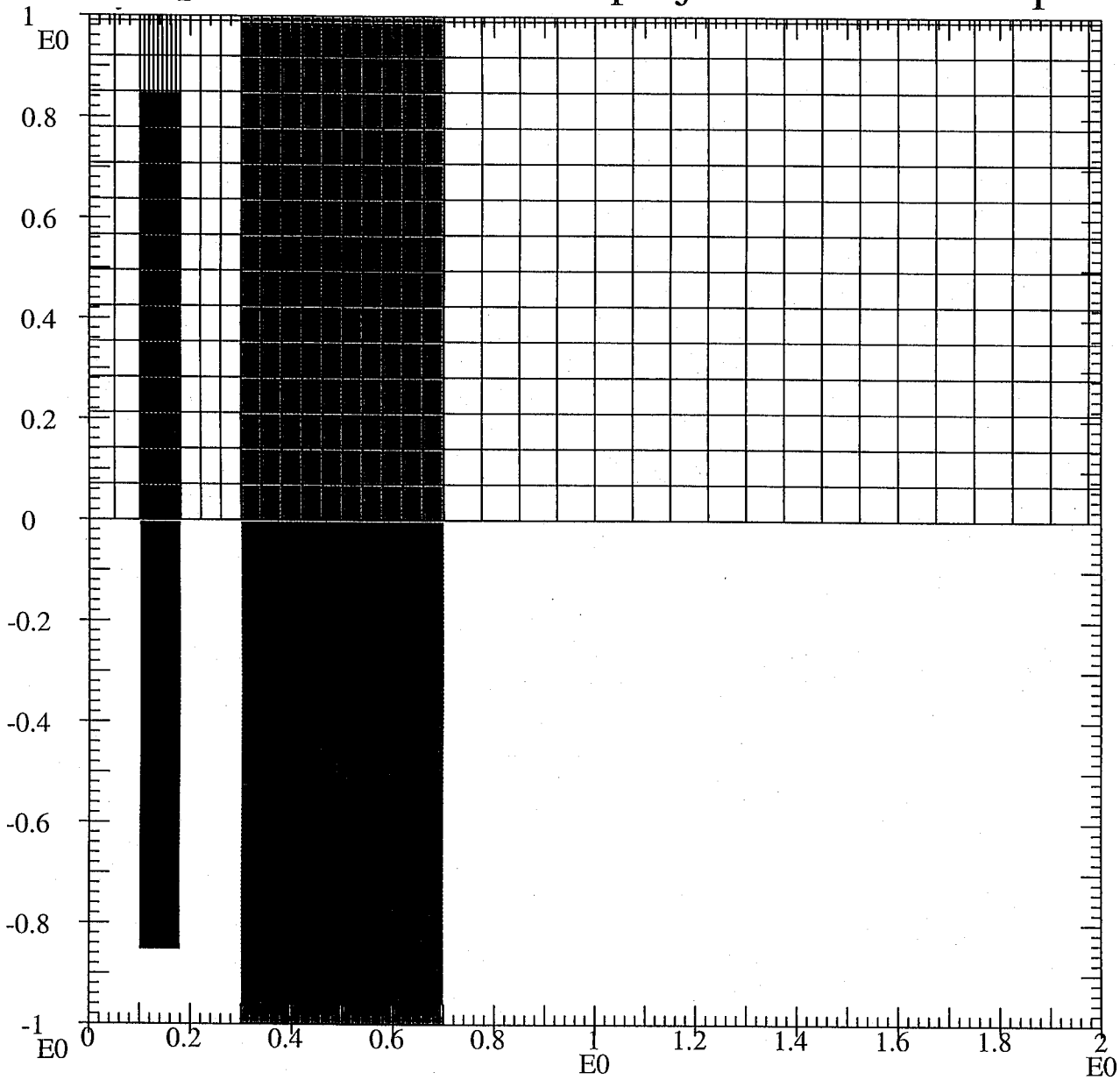
First series NMD EOS experiments modeling calculations

Closeup of 17mm diameter projectile: materials plot and zoning



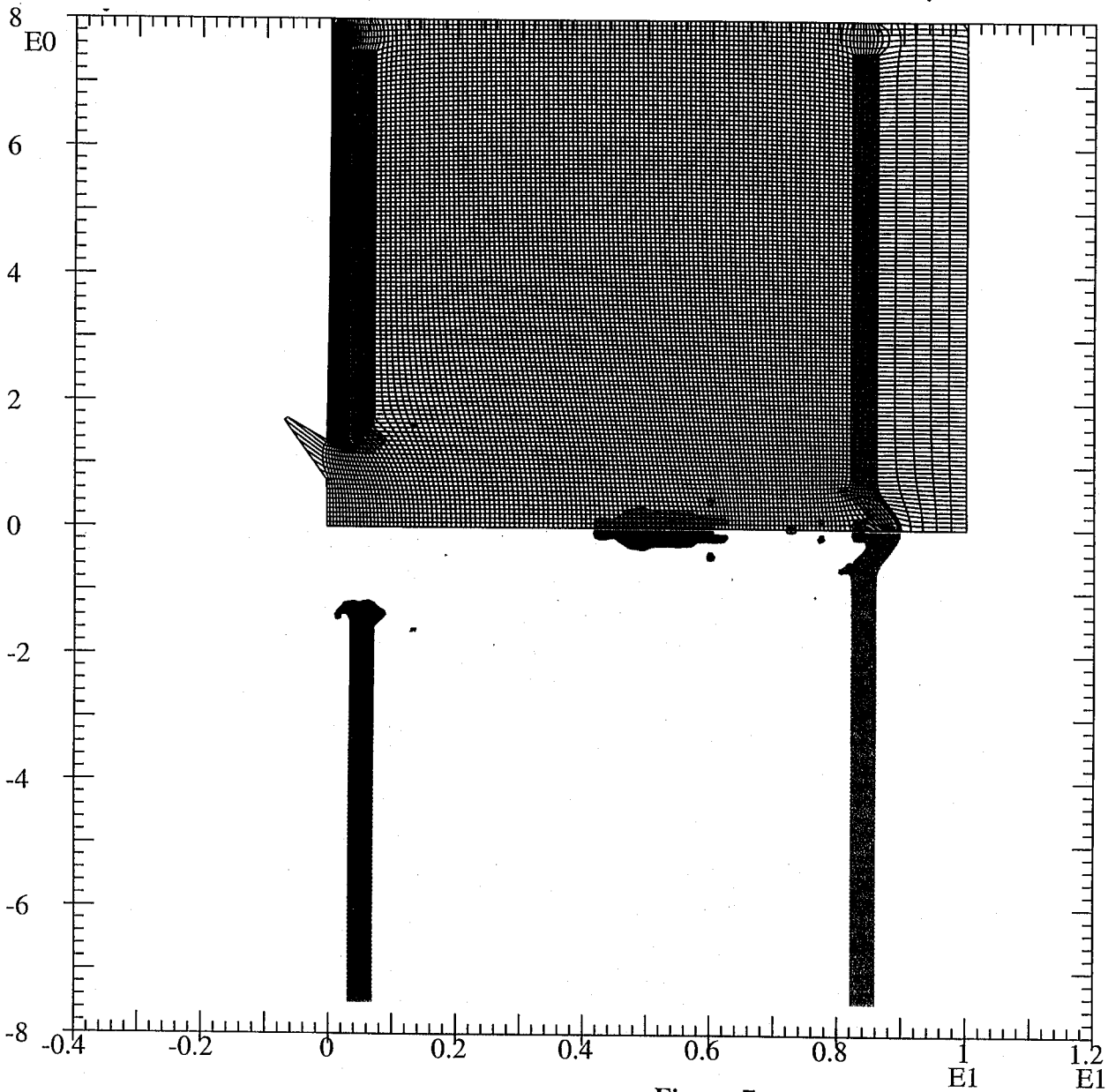
Red: projectile
Green: target
Yellow: vacuum background

nmda-4-mg-6-18-2001

Figure 6

First series NMD EOS experiments modeling calculations

12.7mm diameter projectile at 6km/s:t=20μs materials plot and zoning



Red: projectile
Green: target
Blue: witness plate
Yellow: vacuum background

nmda--7-mg-6-18-2001

Figure 7

First series NMD EOS experiments modeling calculations

12.7mm diameter projectile at 6km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

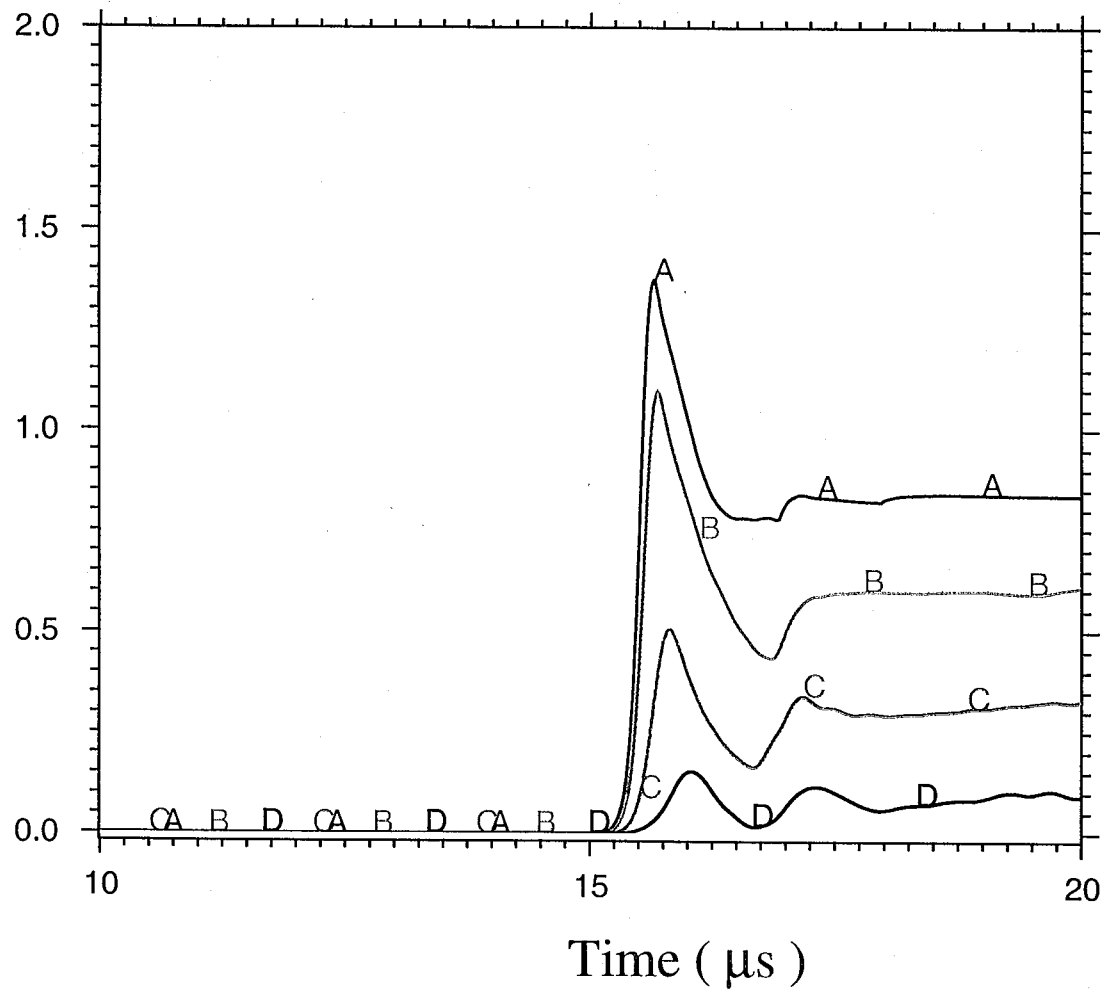


Figure 8

nmda--10-mg-6-21-2001

First series NMD EOS experiments modeling calculations

17mm diameter projectile at 6km/s:t=20μs materials plot and zoning

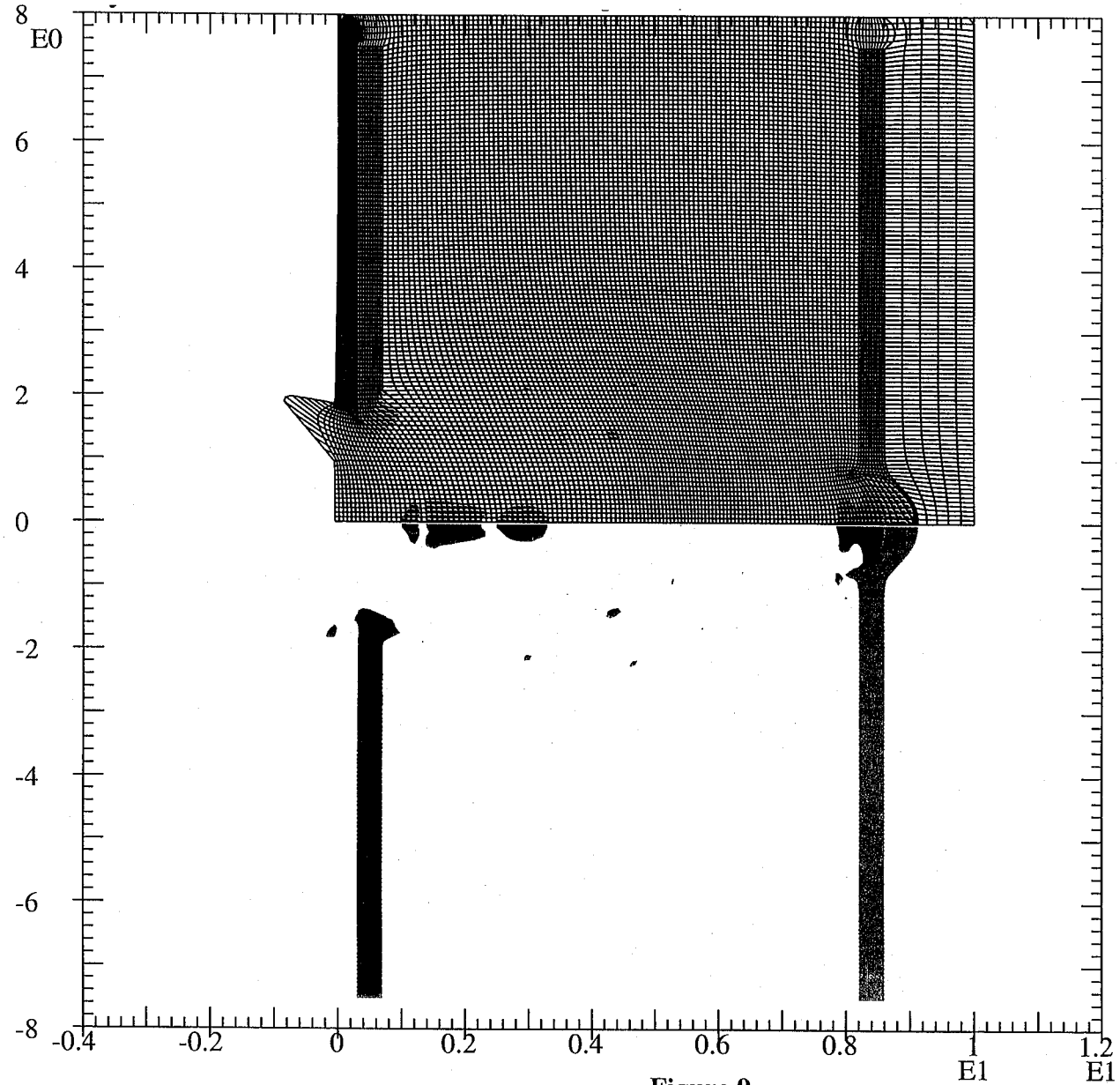


Figure 9

Red: projectile
Green: target
Blue: witness plate
Yellow: vacuum background

nmda--6-mg-6-18-2001

First series NMD EOS experiments modeling calculations

17mm diameter projectile at 6km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

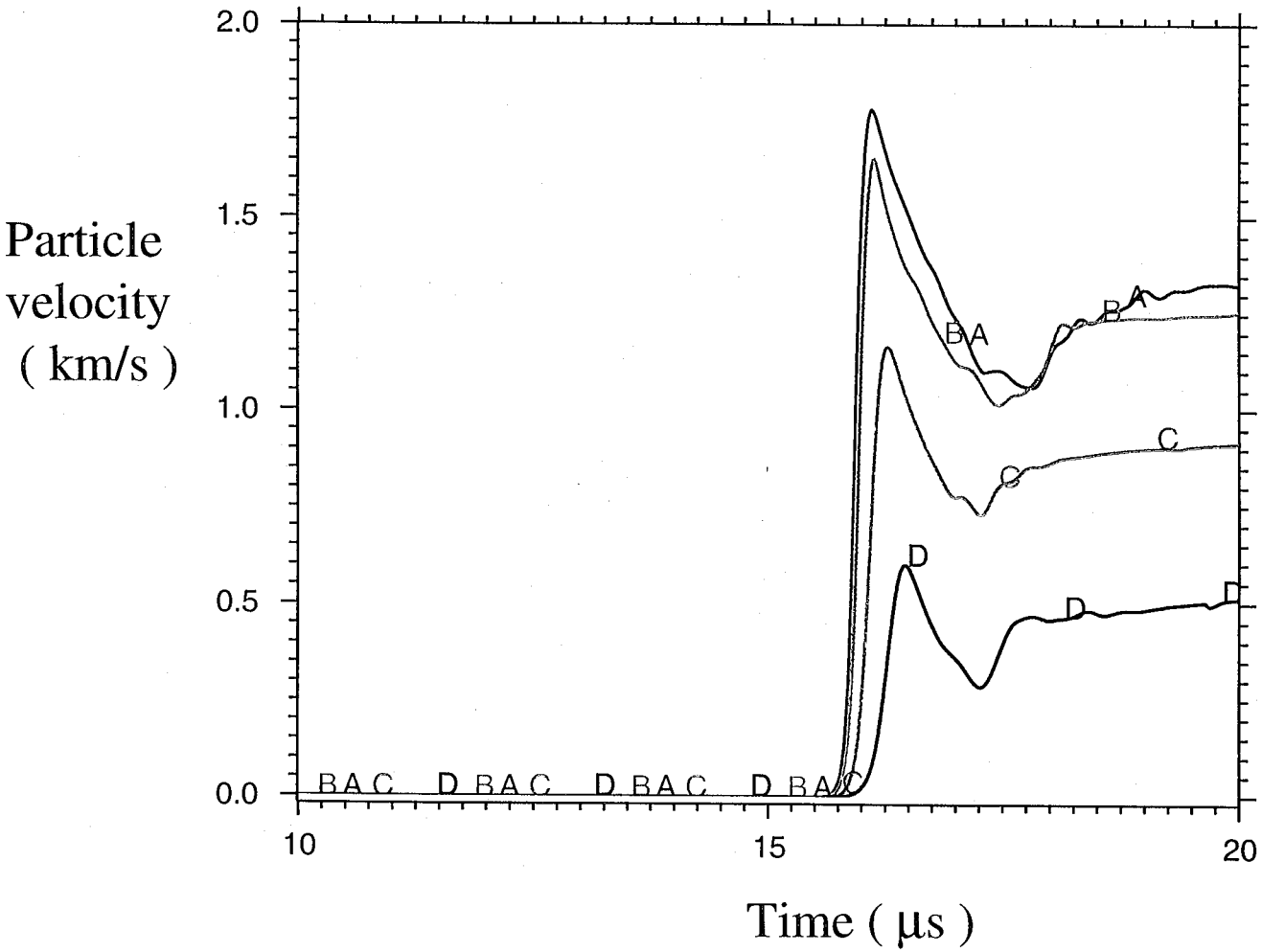
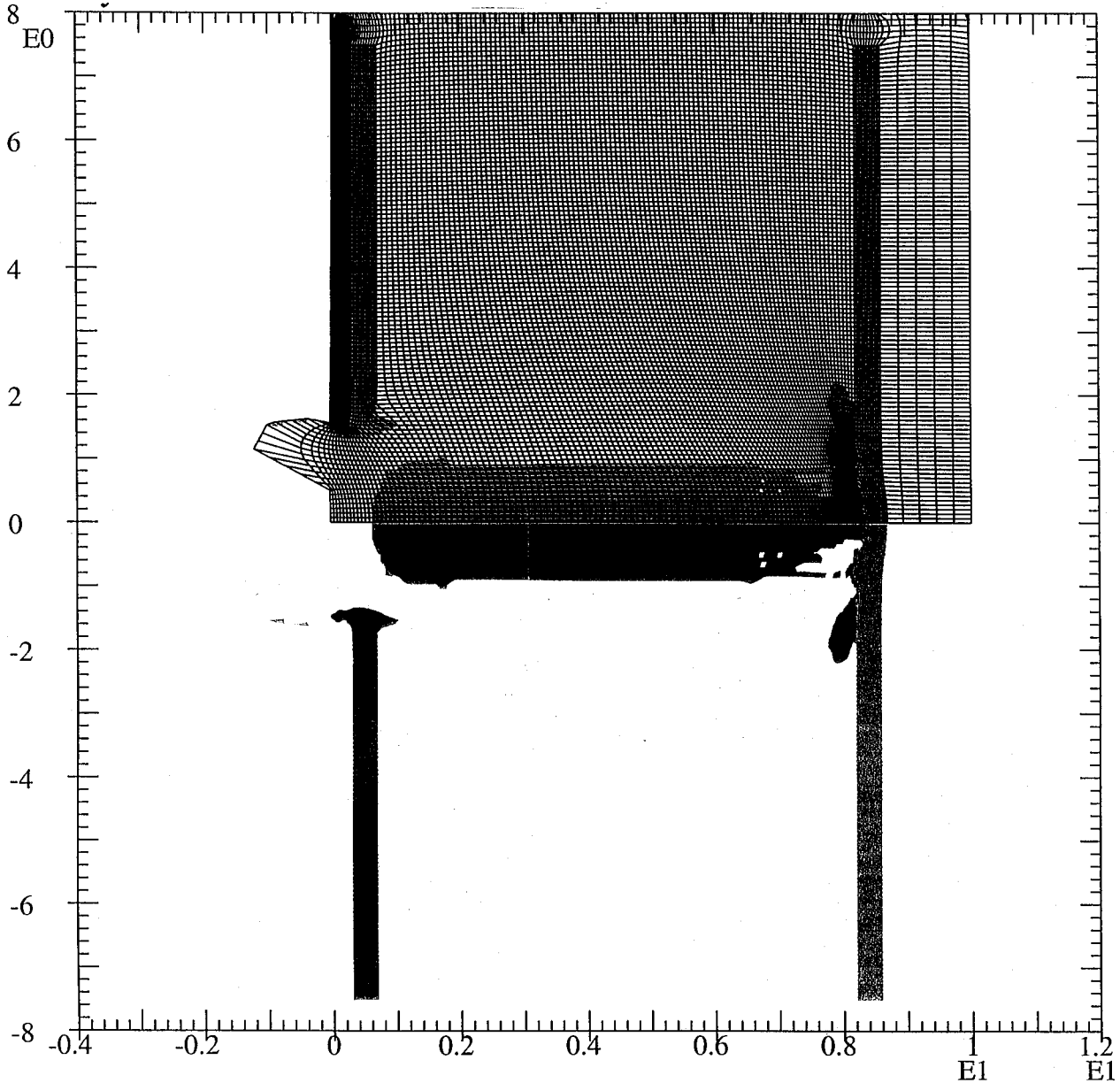


Figure 10

First series NMD EOS experiments modeling calculations

12.7mm diameter projectile at 11km/s:t=12μs materials plot and zoning



Red: projectile
Green: target
Blue: witness plate
Yellow: vacuum background

nmda--8-mg-6-18-2001

Figure 11

First series NMD EOS experiments modeling calculations

12.7mm diameter projectile at 11km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

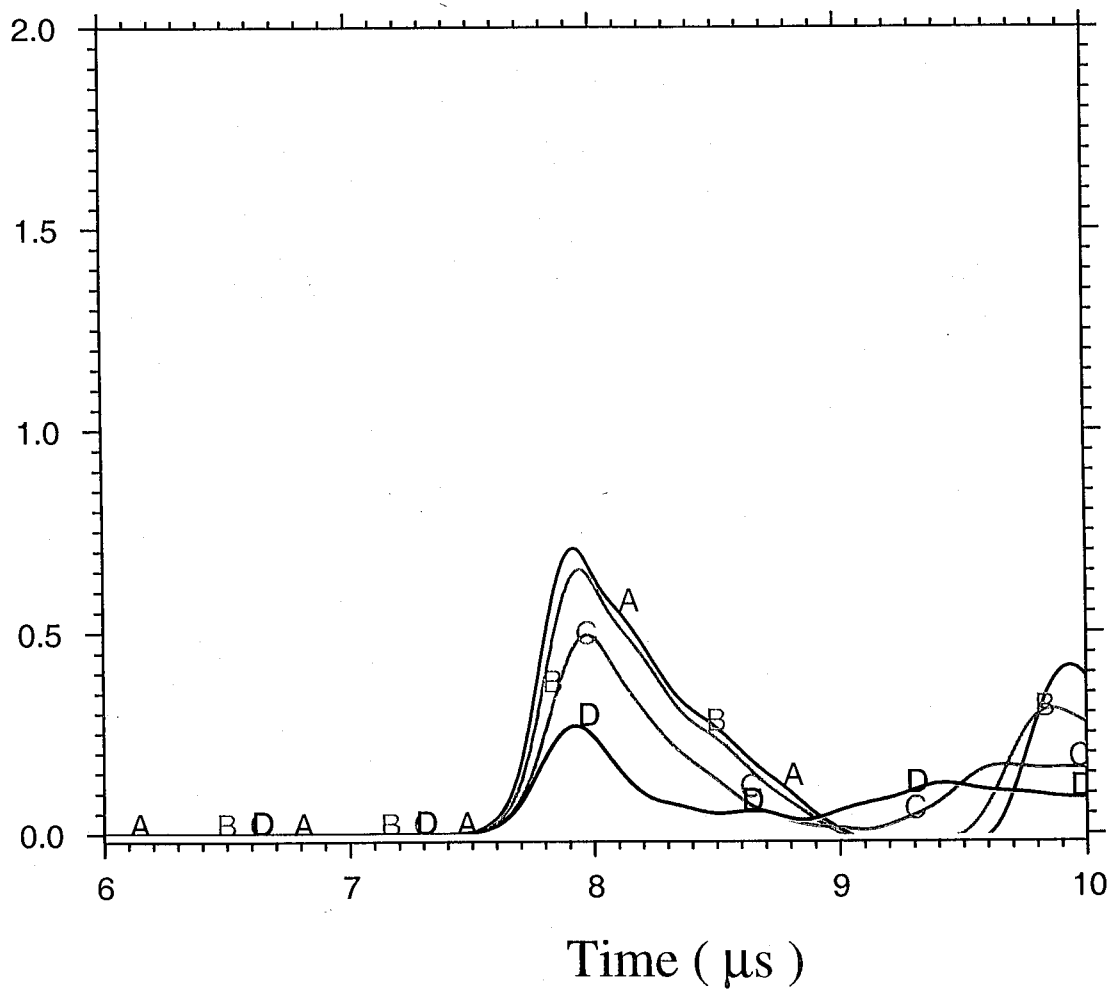
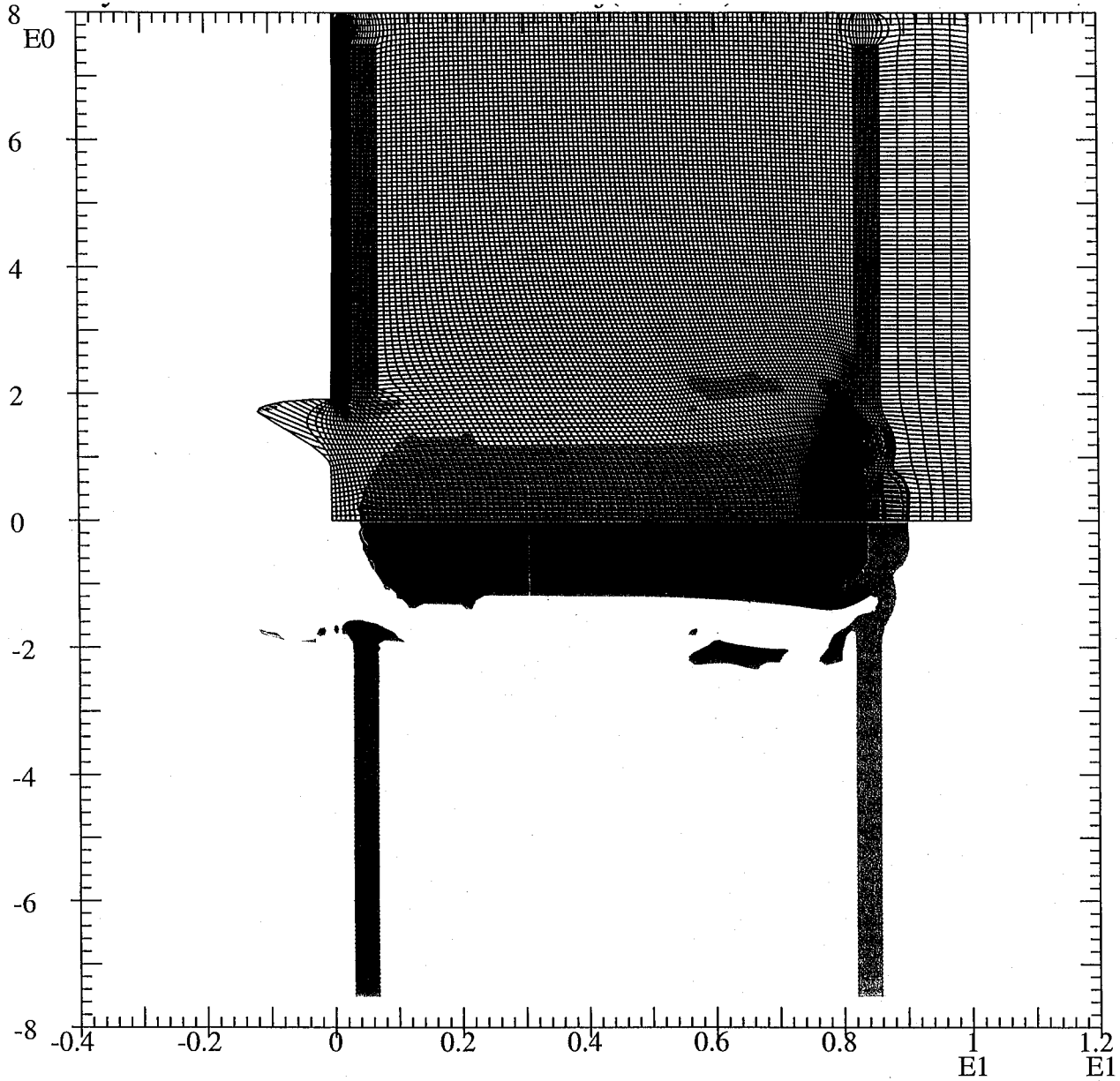


Figure 12

nmda--12-mg-6-21-2001

First series NMD EOS experiments modeling calculations

17mm diameter projectile at 11km/s:t=12μs materials plot and zoning



Red: projectile
Green: target
Blue: witness plate
Yellow: vacuum background

nmda--9-mg-6-18-2001

Figure 13

First series NMD EOS experiments modeling calculations

17mm diameter projectile at 11km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

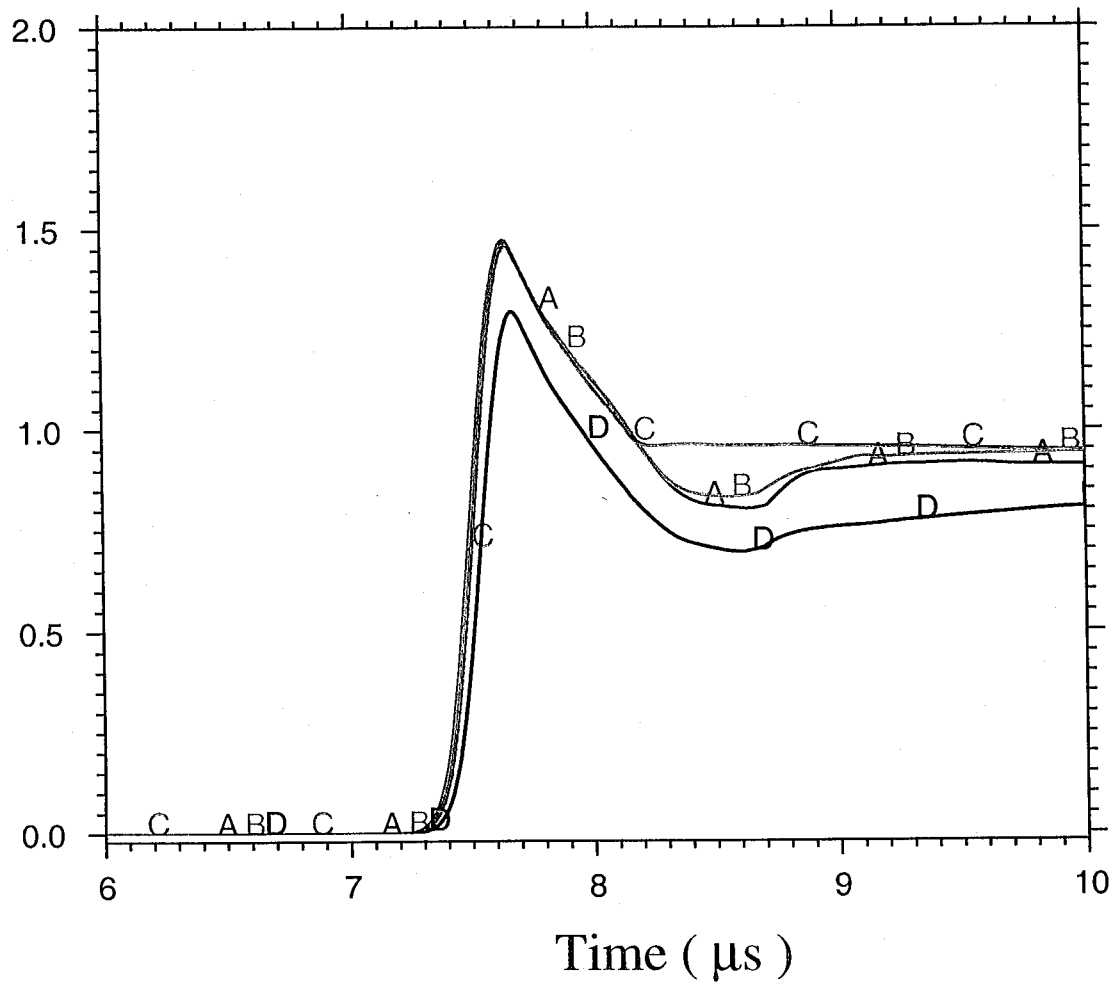
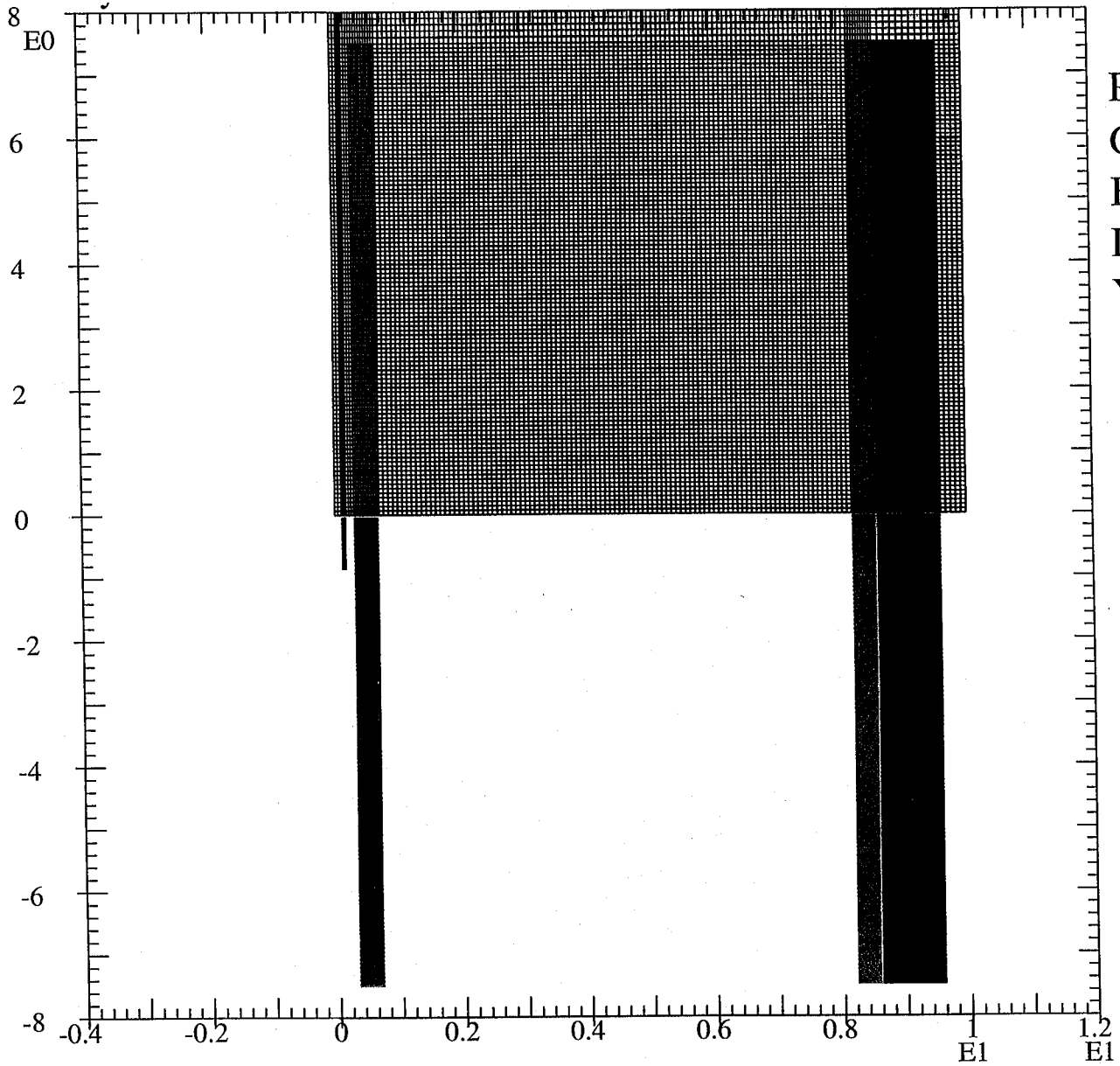


Figure 14

nmda--13-mg-6-21-2001

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm dia. proj. materials plot and zoning



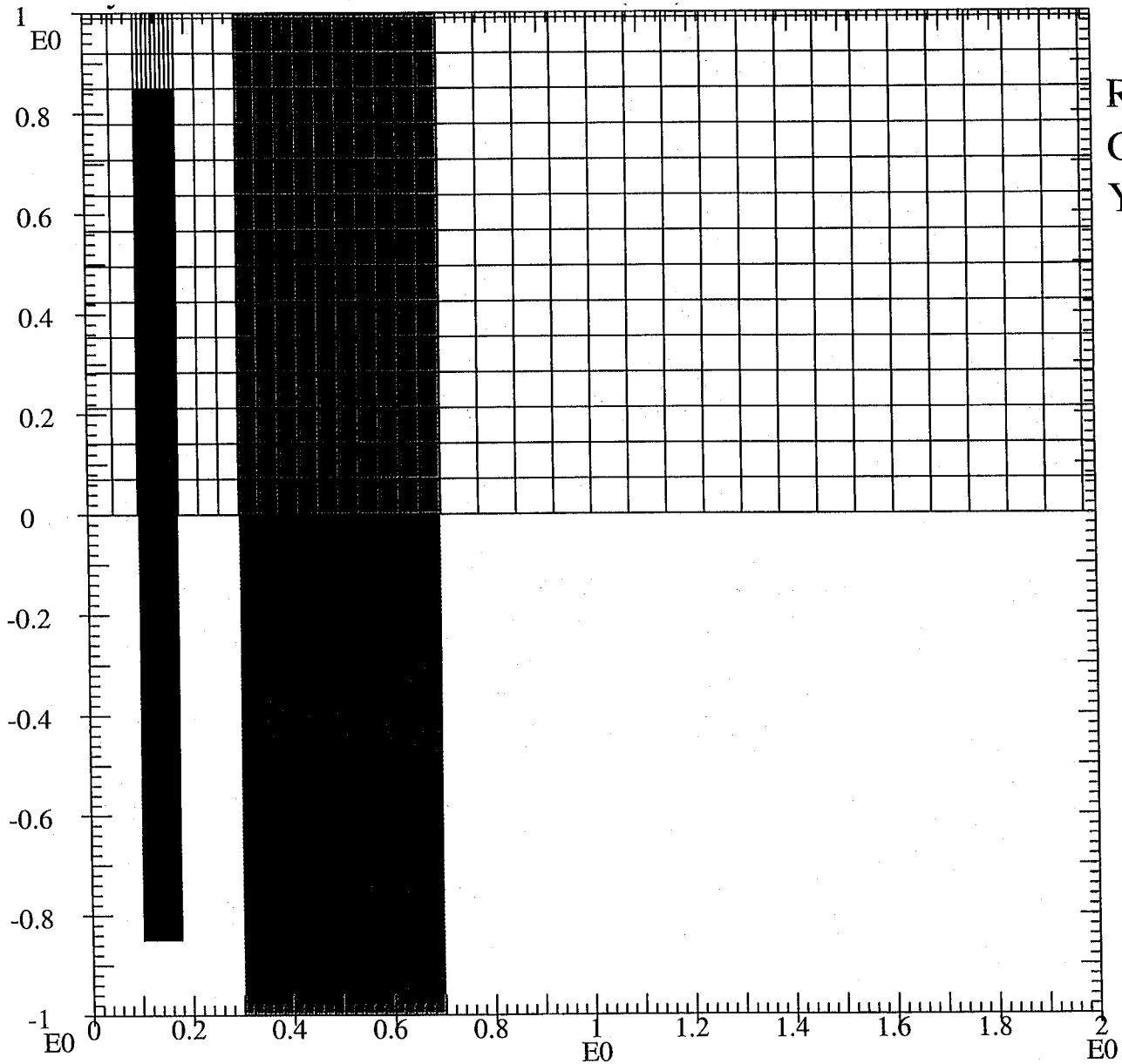
Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--14-mg-6-21-2001

Figure 15

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm diameter projectile closeup



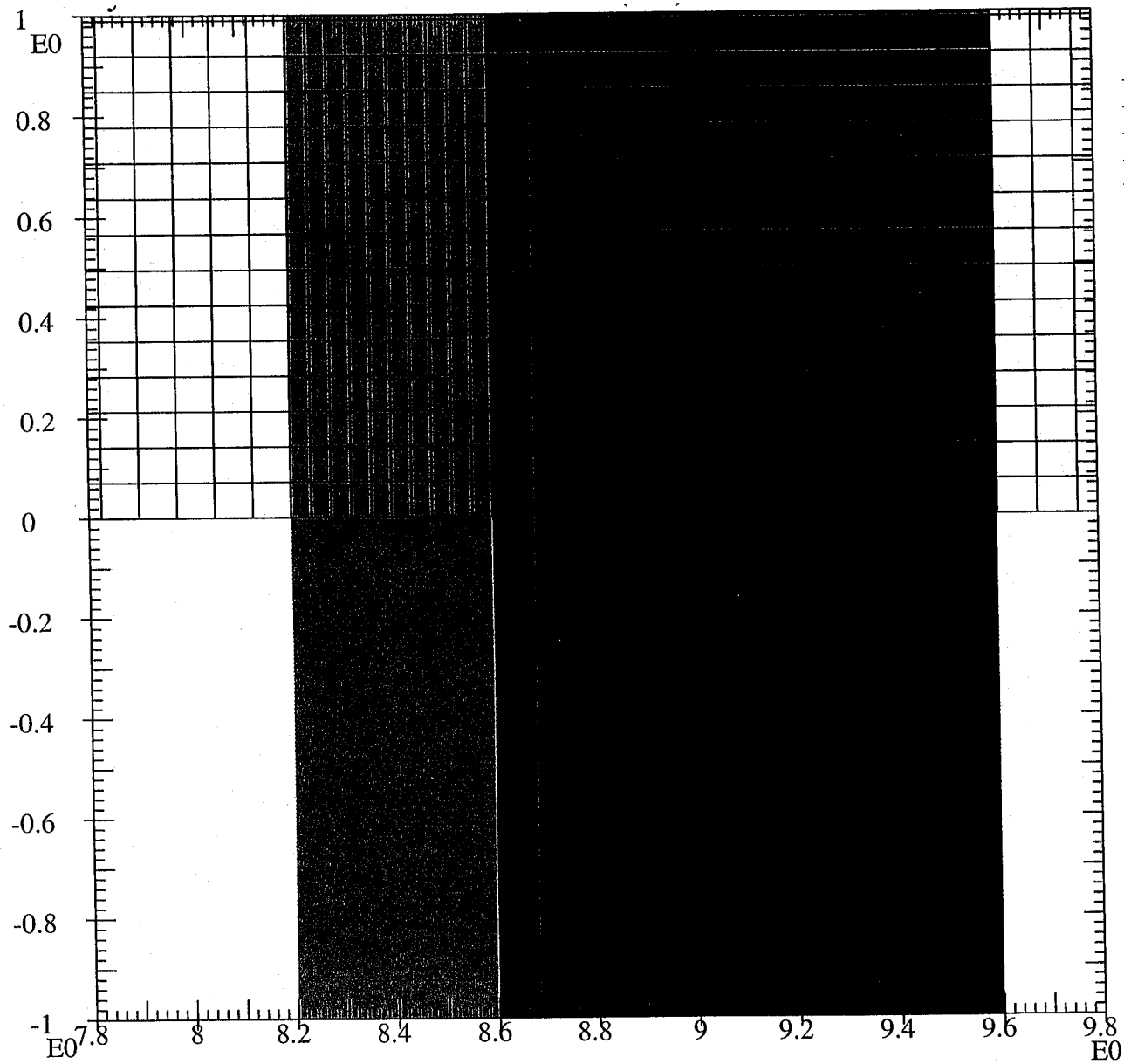
Red: projectile
Green: target
Yellow: vacuum background

nmda--15-mg-6-21-2001

Figure 16

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) closeup of witness plate and backing



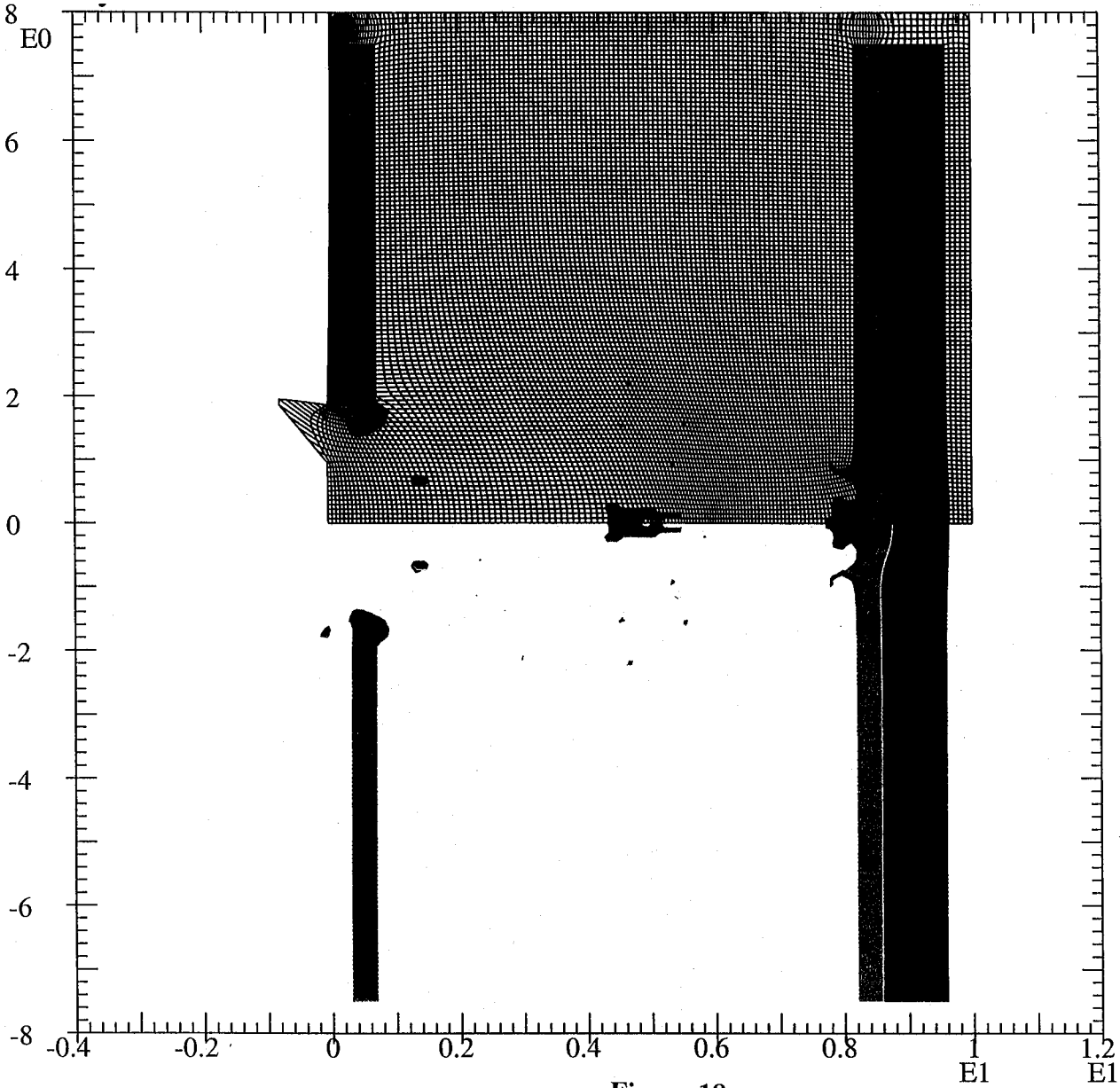
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--16-mg-6-21-2001

Figure 17

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm dia. proj. at 6km/s: t=20μs



Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--17-mg-6-21-2001

Figure 18

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm diameter projectile at 6km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

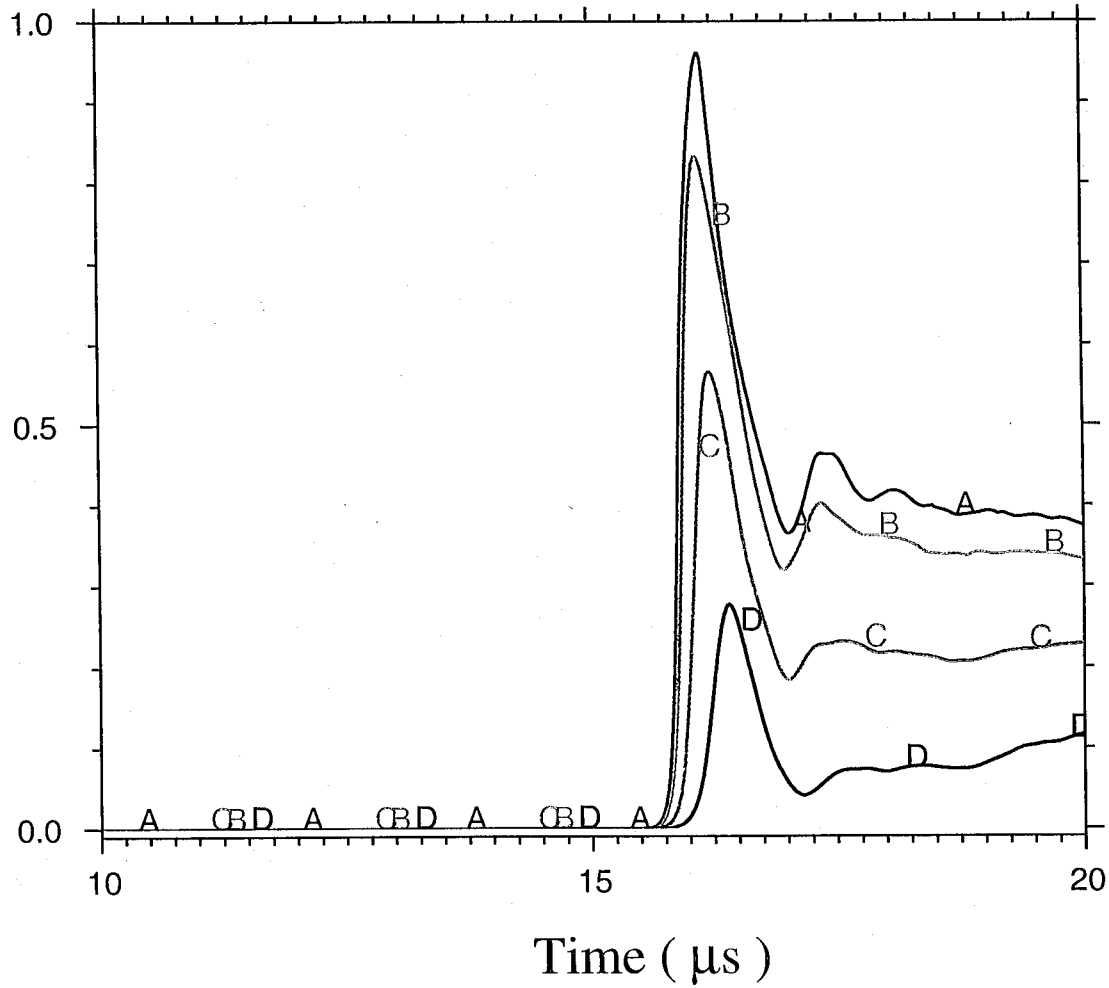
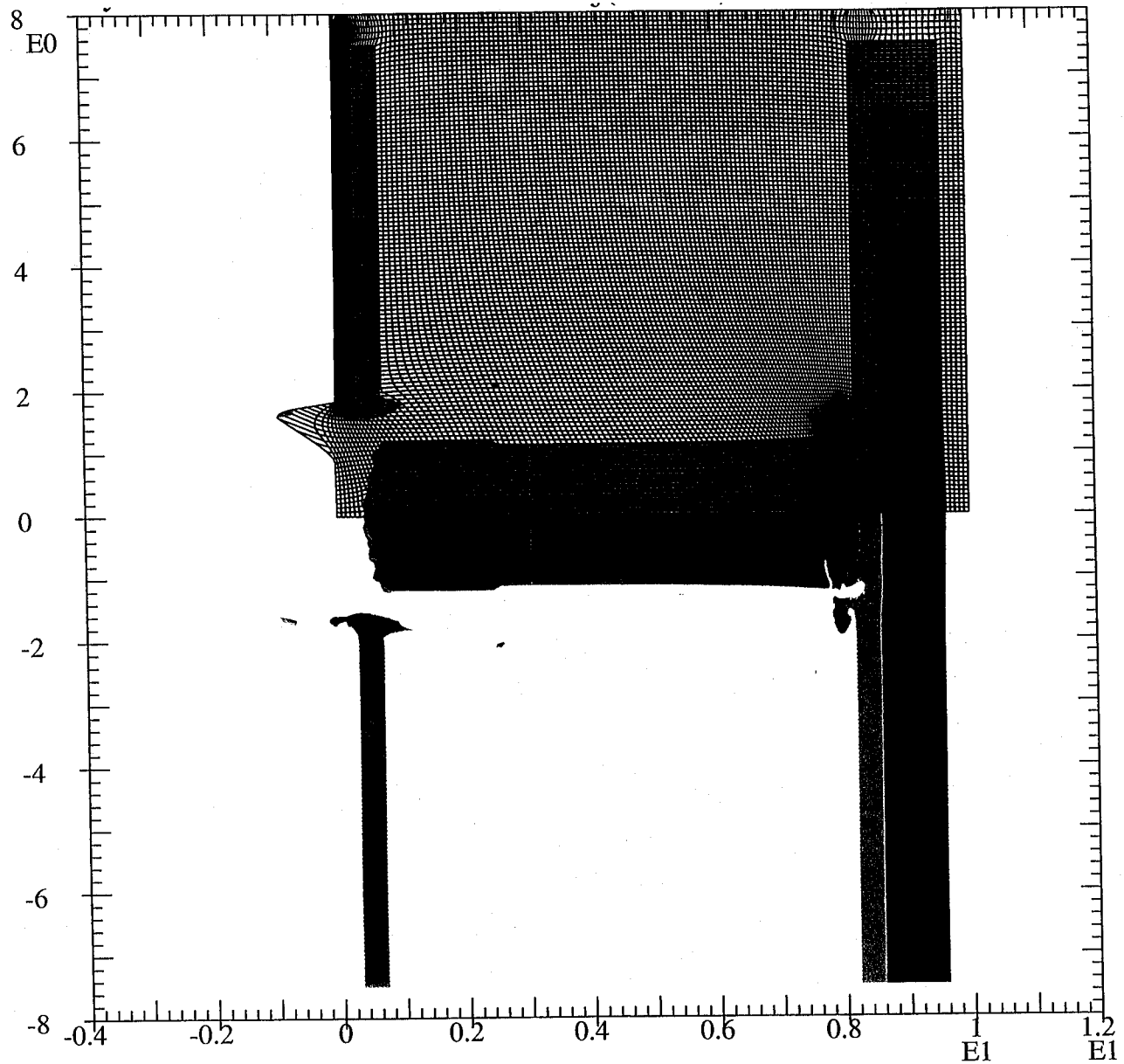


Figure 19

nmda--18-mg-6-21-2001

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm dia. proj. at 11km/s: t=10μs



Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--19-mg-6-21-2001

Figure 20

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm diameter projectile at 11km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

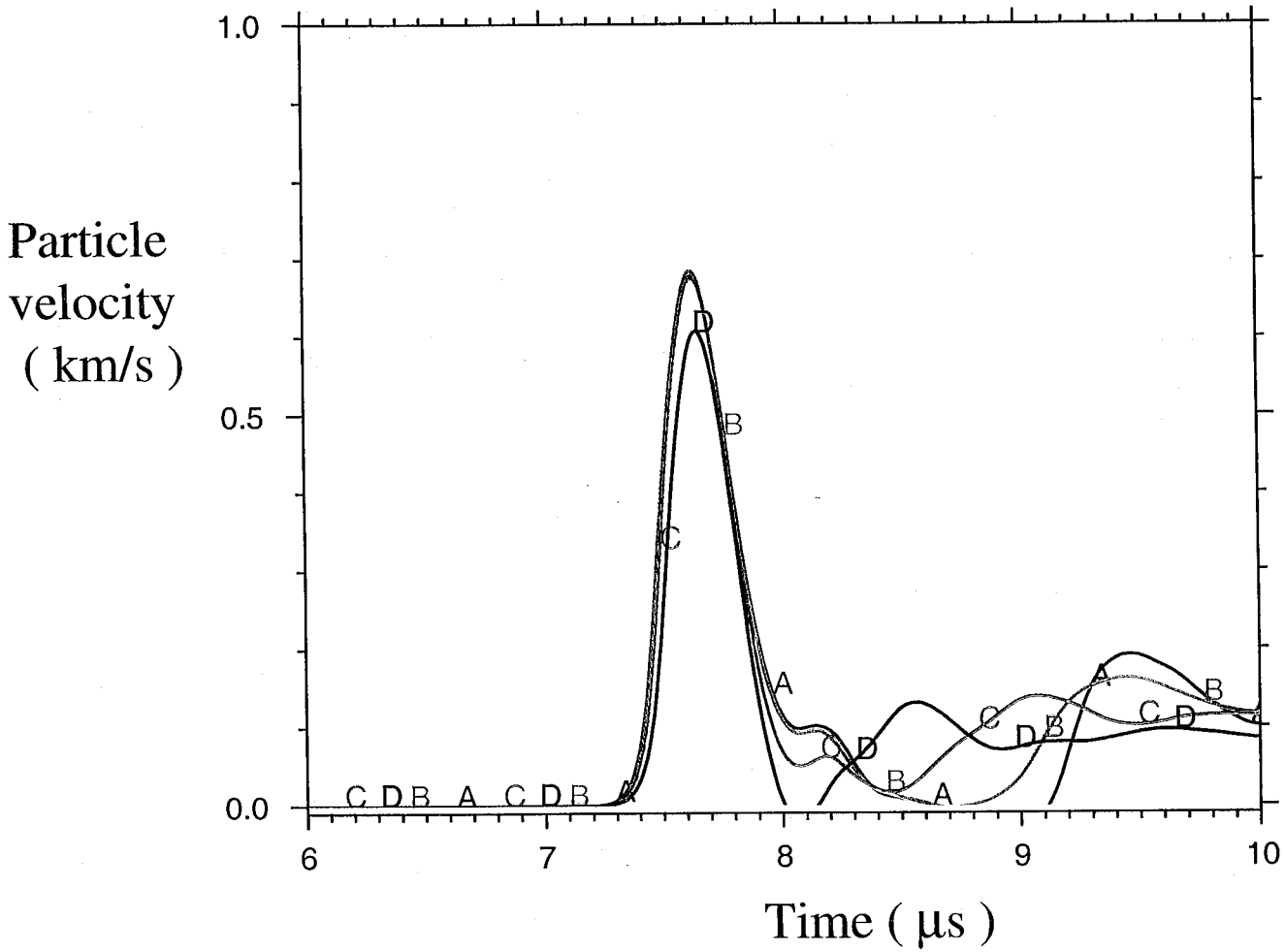
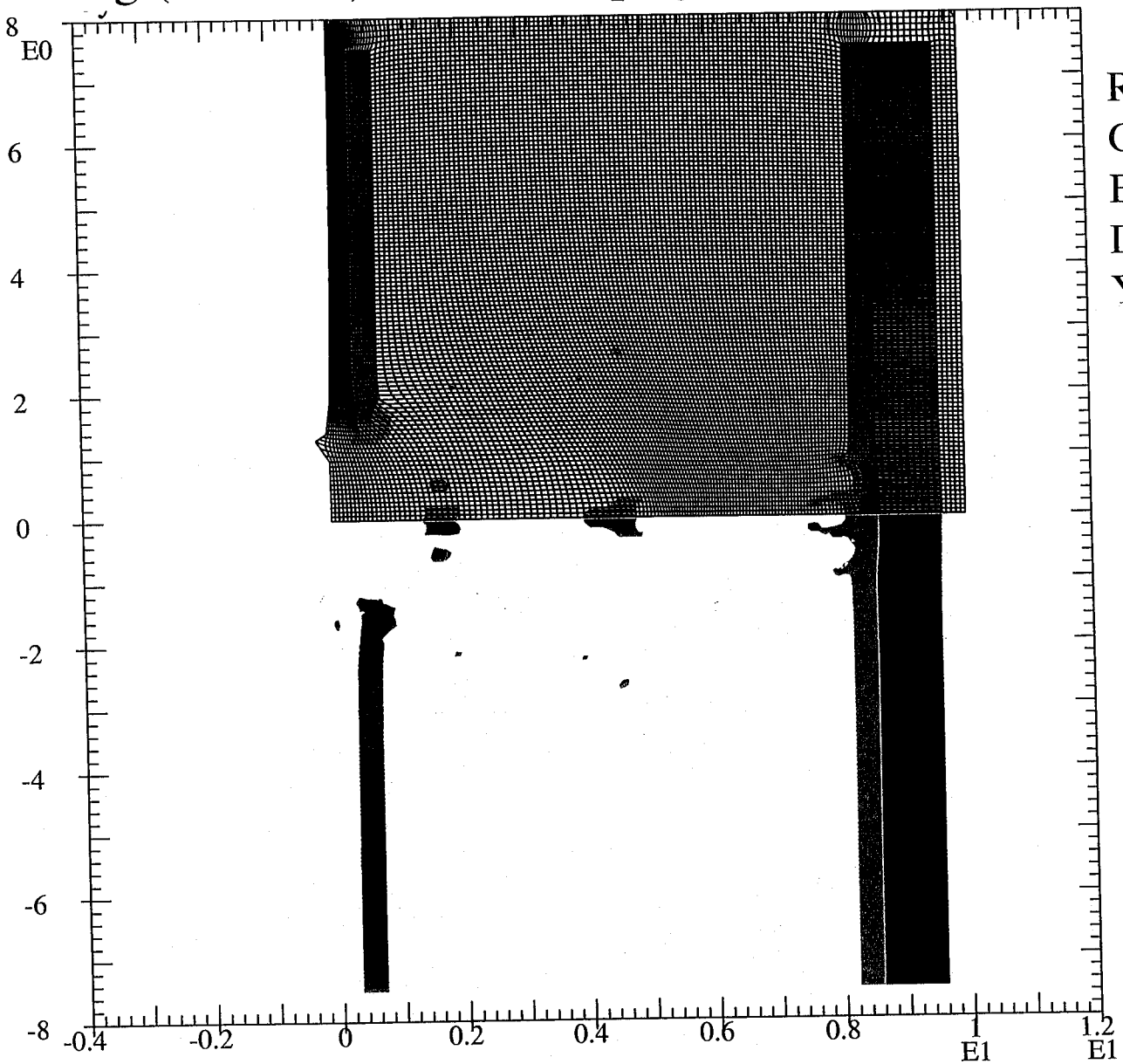


Figure 21

nmda--20-mg-6-21-2001

Second series NMD EOS experiments modeling calculations

St. zoning (150x113) 17mm dia. proj. at 6km/s target strength X2: t=22μs



Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--31-mg-6-22-2001

Figure 22

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm dia. proj. 6km/s target strength X2
Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

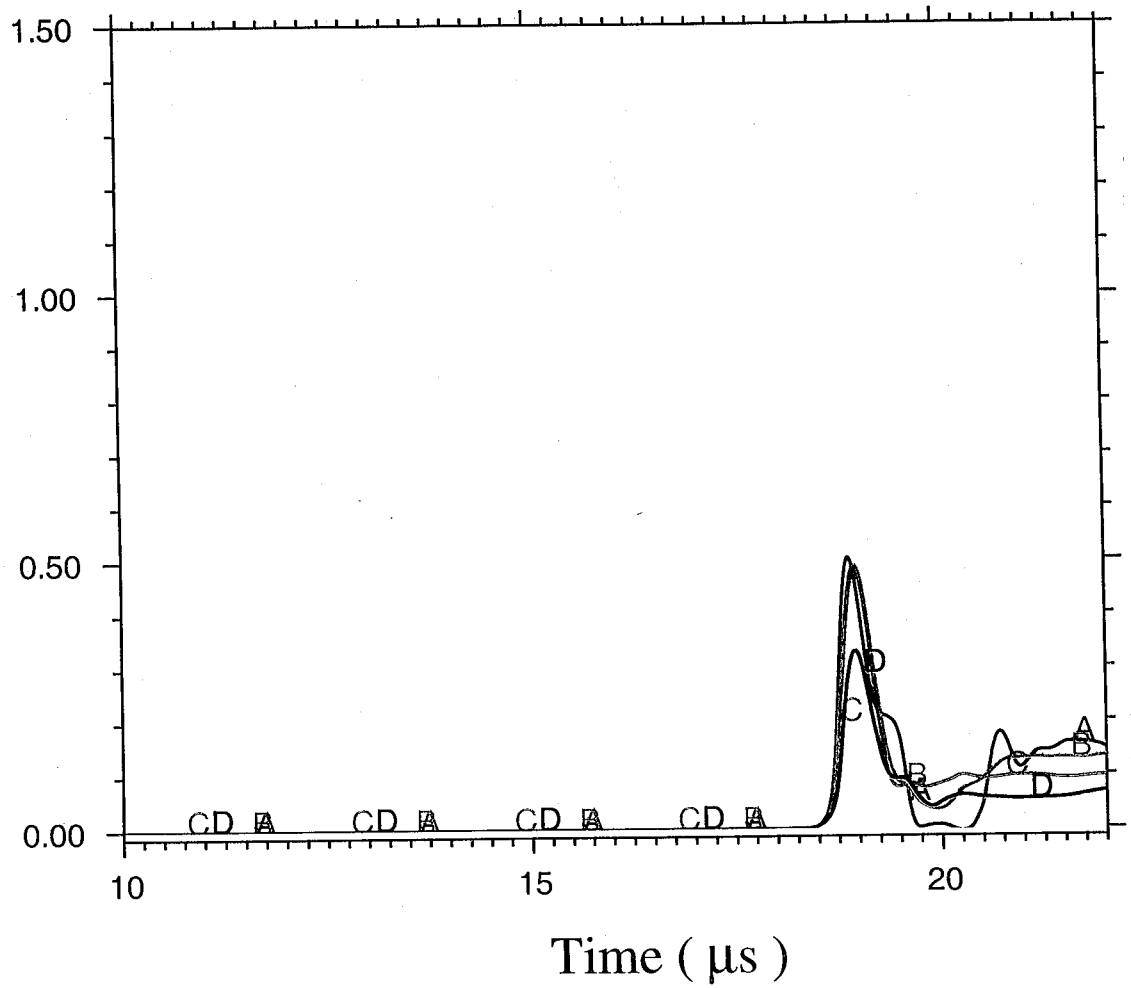
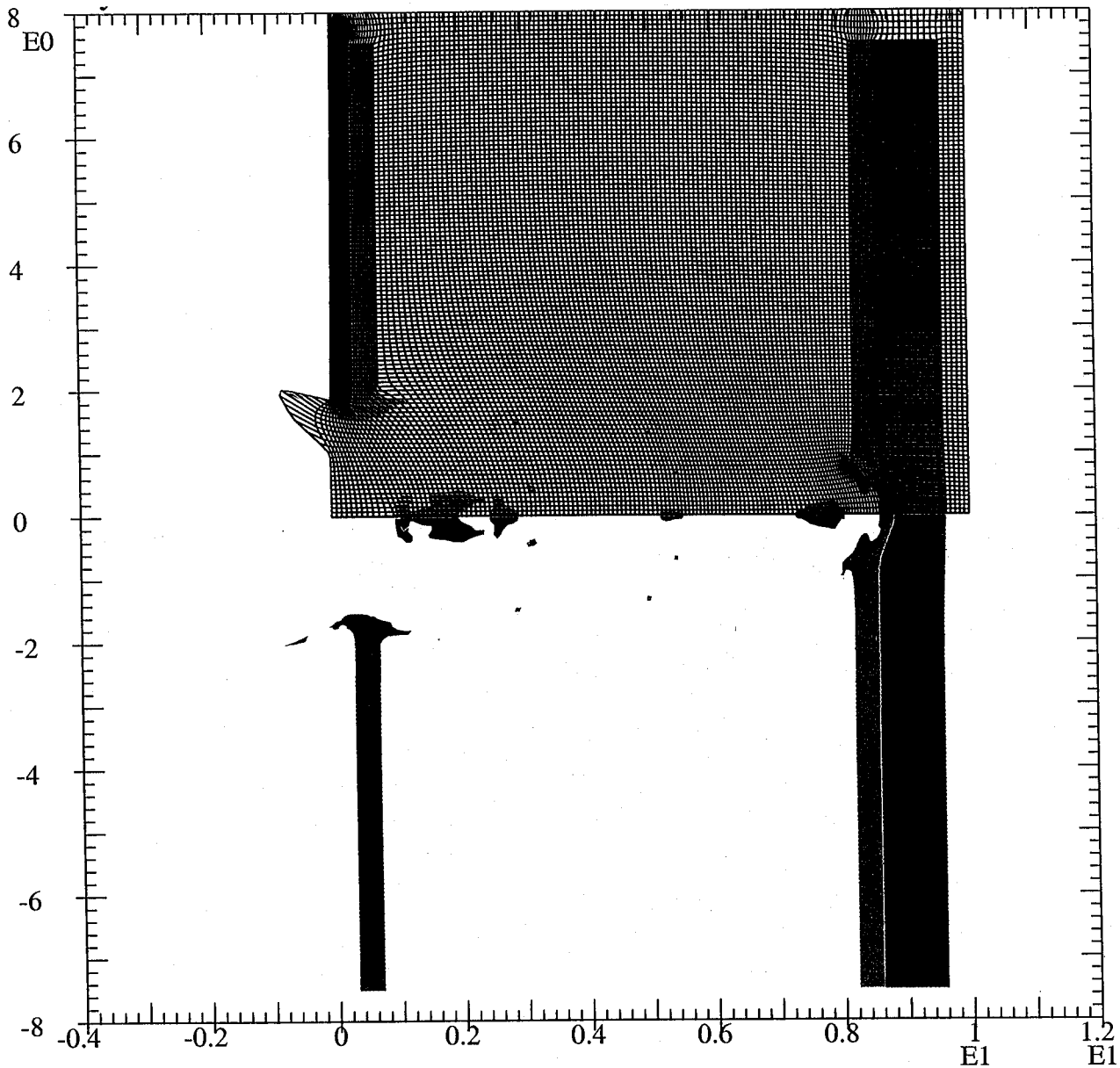


Figure 23

nmda--28-mg-6-22-2001

Second series NMD EOS experiments modeling calculations

St. zoning (150x113) 17mm dia. proj. at 6km/s target strength X0.5: t=20μs



Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--32-mg-6-22-2001

Figure 24

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm dia. proj. 6km/s target strength X0.5
Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

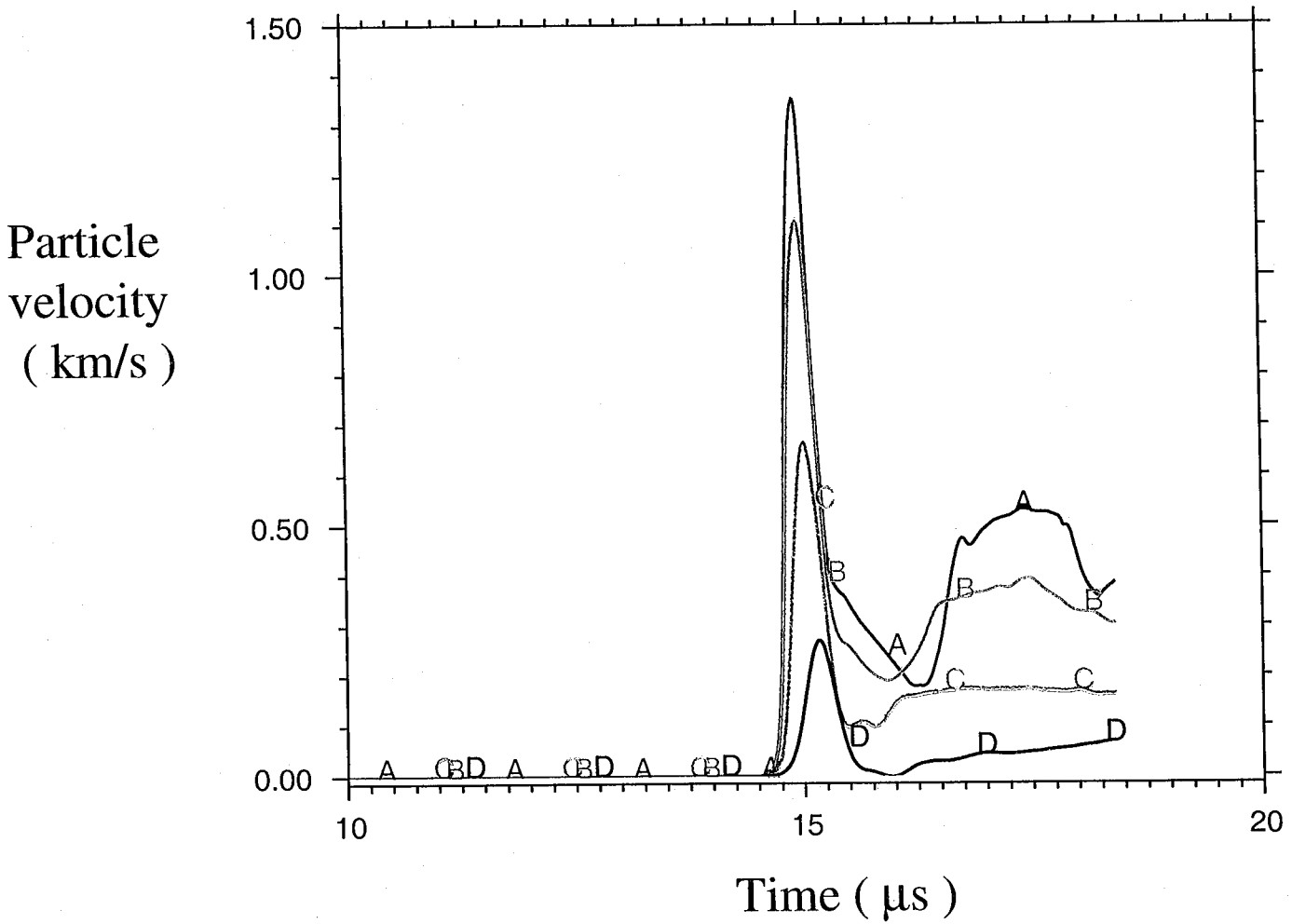
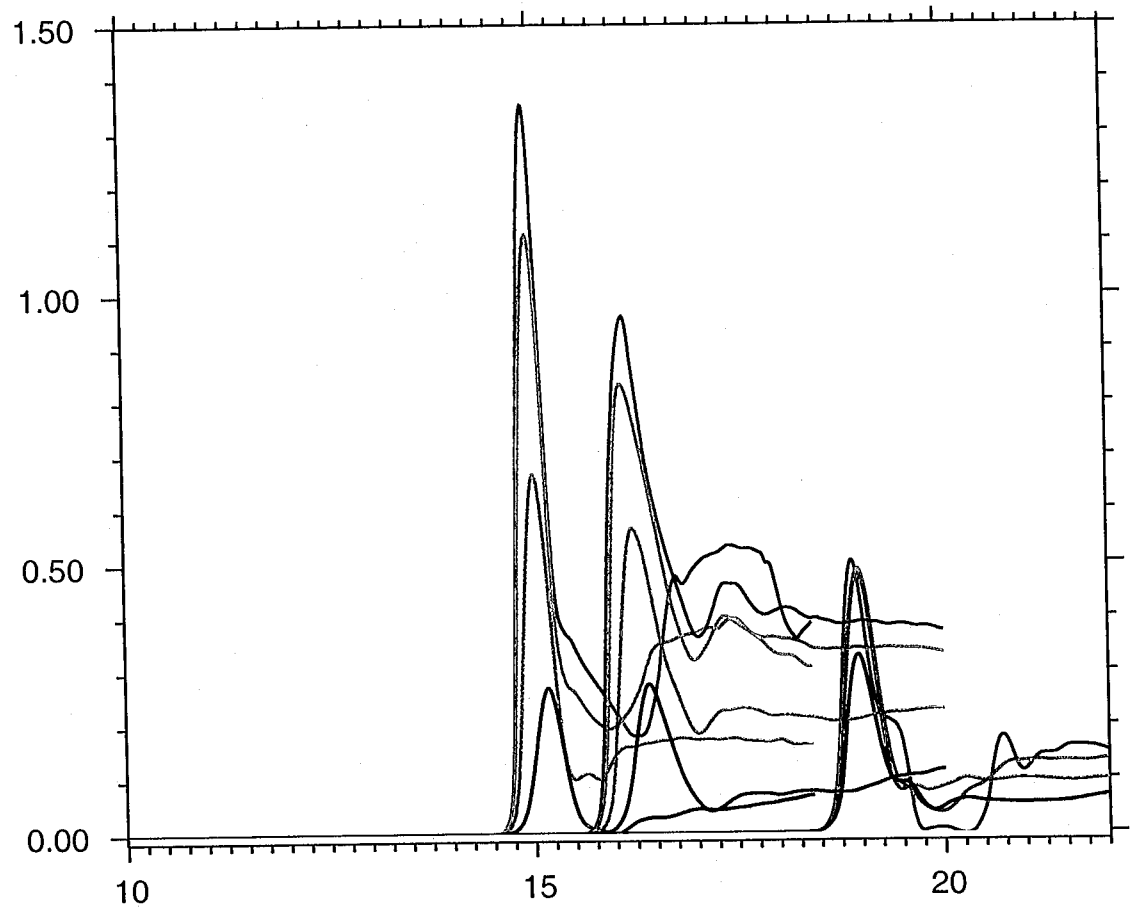


Figure 25

Second series NMD EOS experiments modeling calculations: particle velocity profile dependence on target strength

Standard zoning (150x113) 17mm diameter projectile 6km/s
Particle velocities at rear of witness plate on axis and 2,4 and 6mm away
Early large peaks for target strength X0.5, late small ones for target strength X2

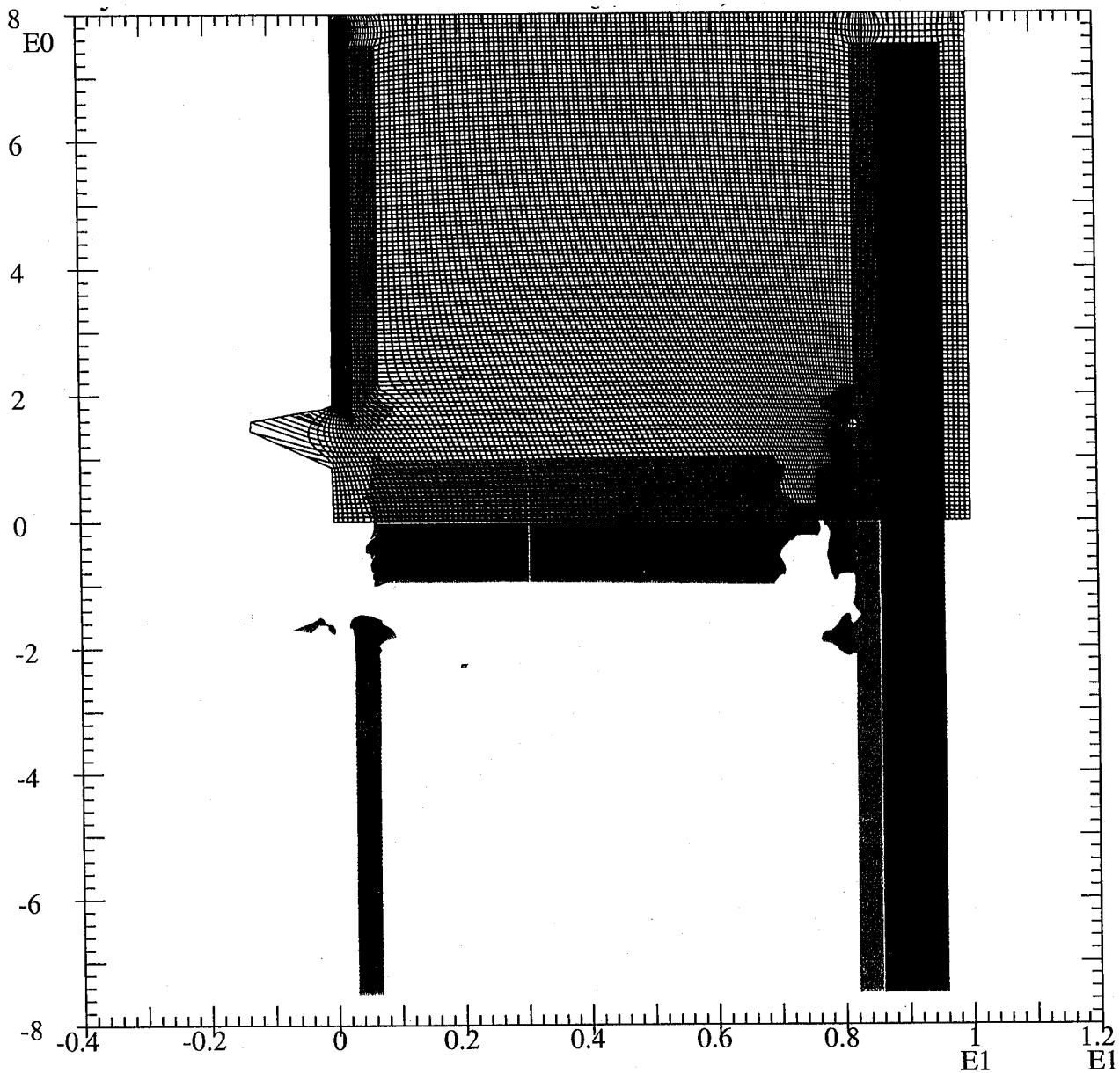


nmda--30-mg-6-22-2001

Figure 26

Second series NMD EOS experiments modeling calculations

St. zoning (150x113) 17mm dia. proj. 11km/s target strength X2: t=11μs



Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--33-mg-7-2-2001

Figure 27

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm dia. proj. 11km/s target strength X2

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

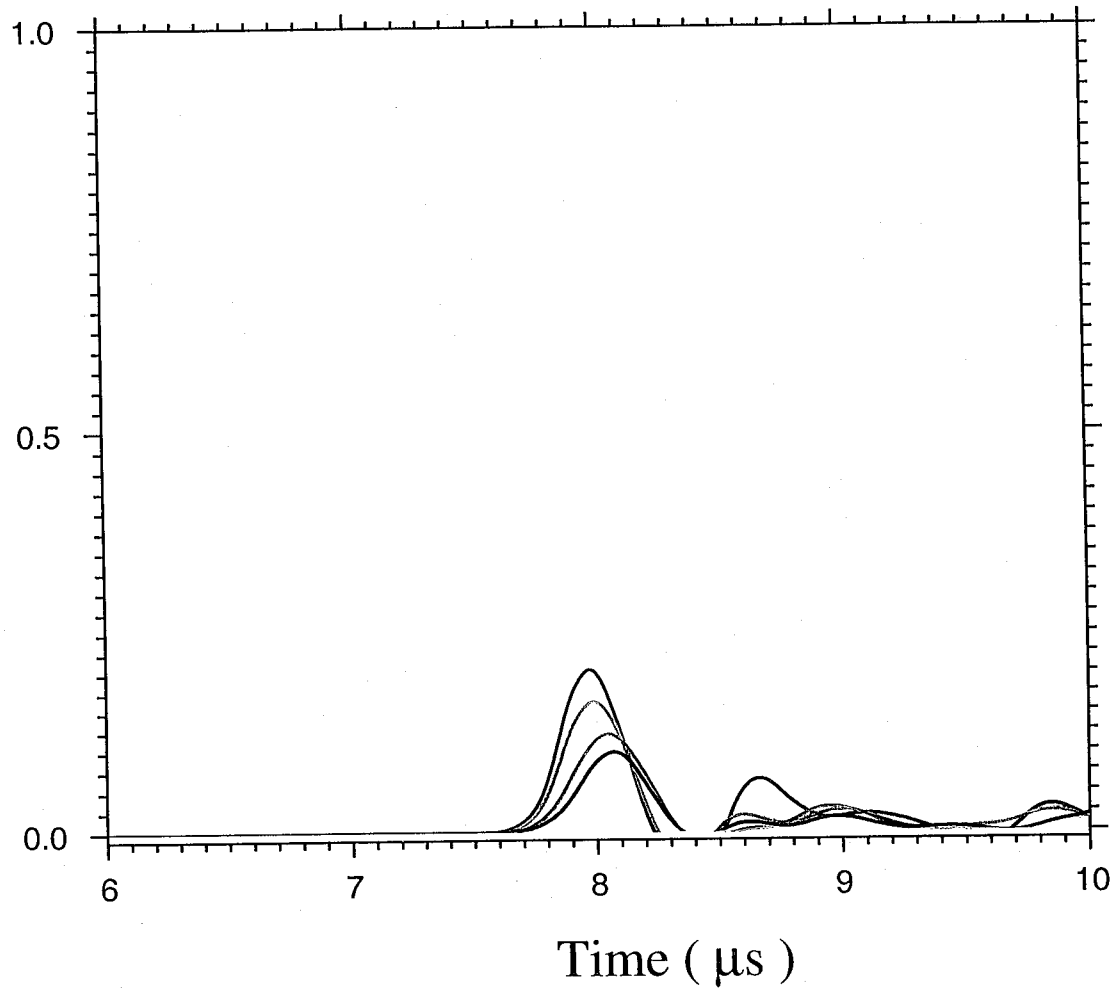
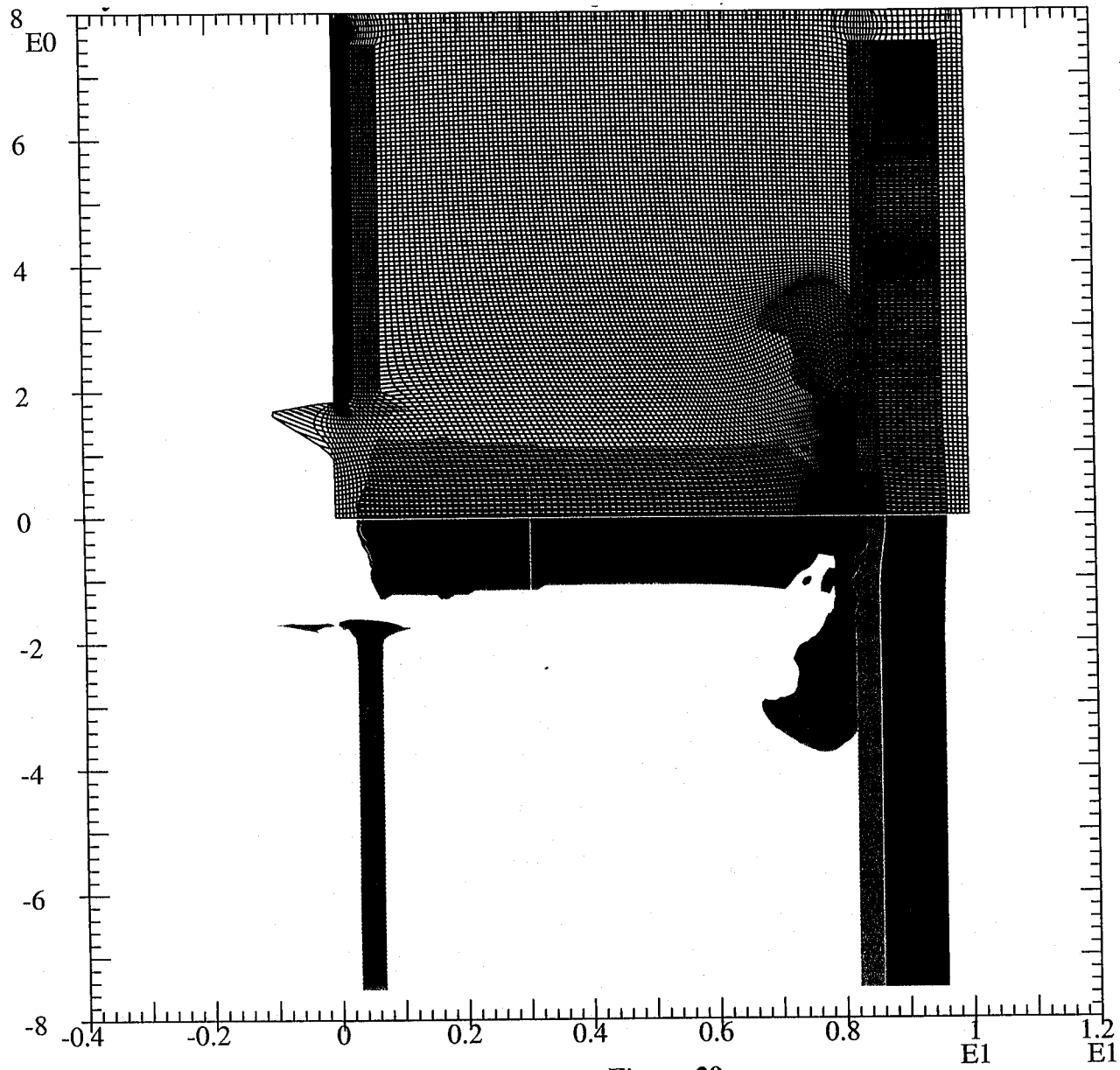


Figure 28

nmda--34-mg-7-2-2001

Second series NMD EOS experiments modeling calculations

St. zoning (150x113) 17mm dia. proj. 11km/s target strength X0.5: t=10μs



Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--35-mg-7-2-2001

Figure 29

Second series NMD EOS experiments modeling calculations

Standard zoning (150x113) 17mm dia. proj. 11km/s target strength X0.5

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

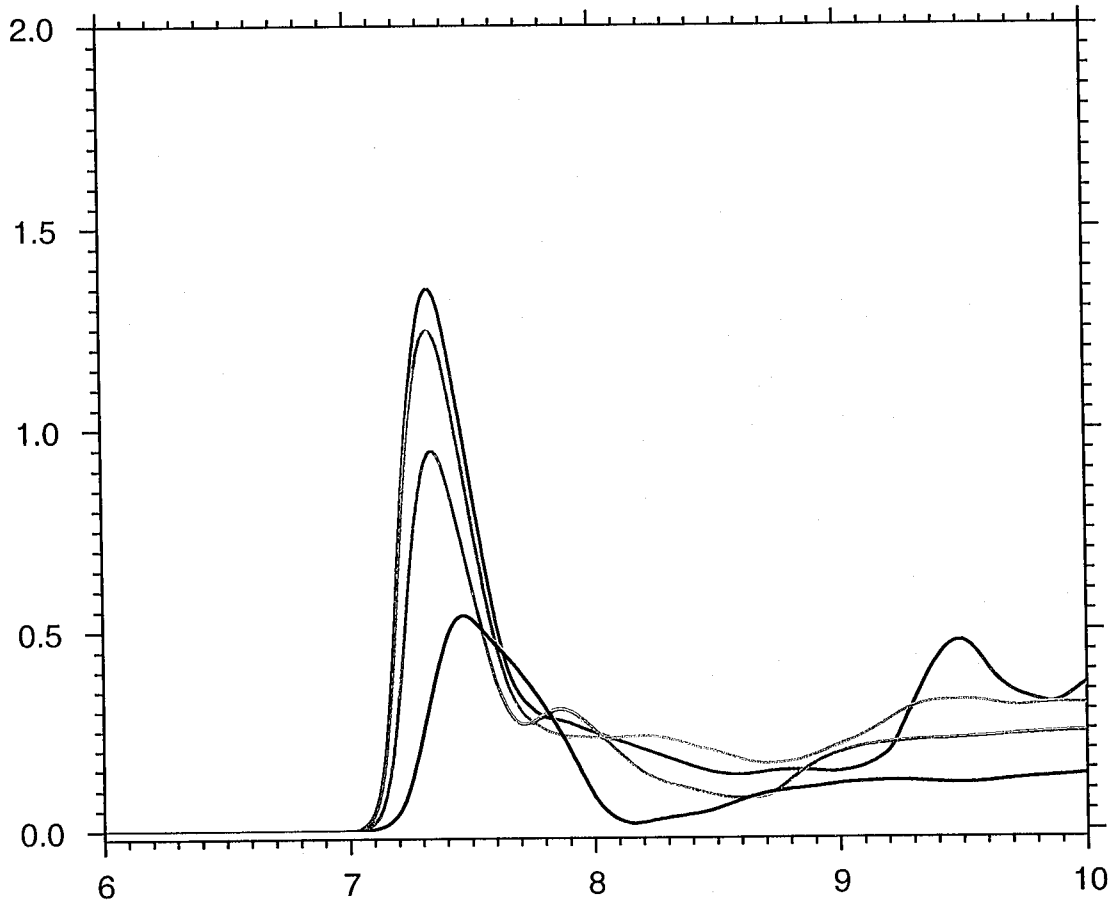


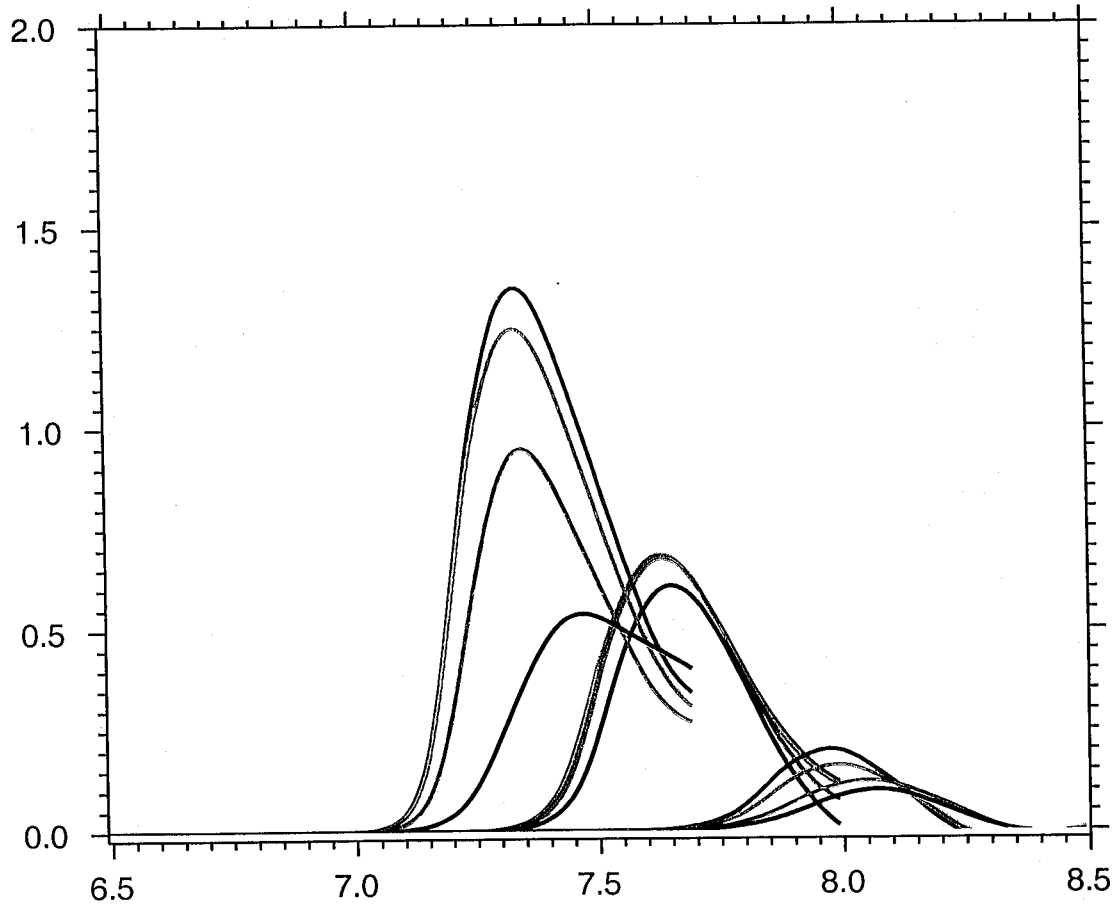
Figure 30

Second series NMD EOS experiments modeling calculations: particle velocity profile dependence on target strength

Standard zoning (150x113) 17mm diameter projectile 11km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

Early large peaks for target strength X0.5, late small ones for target strength X2

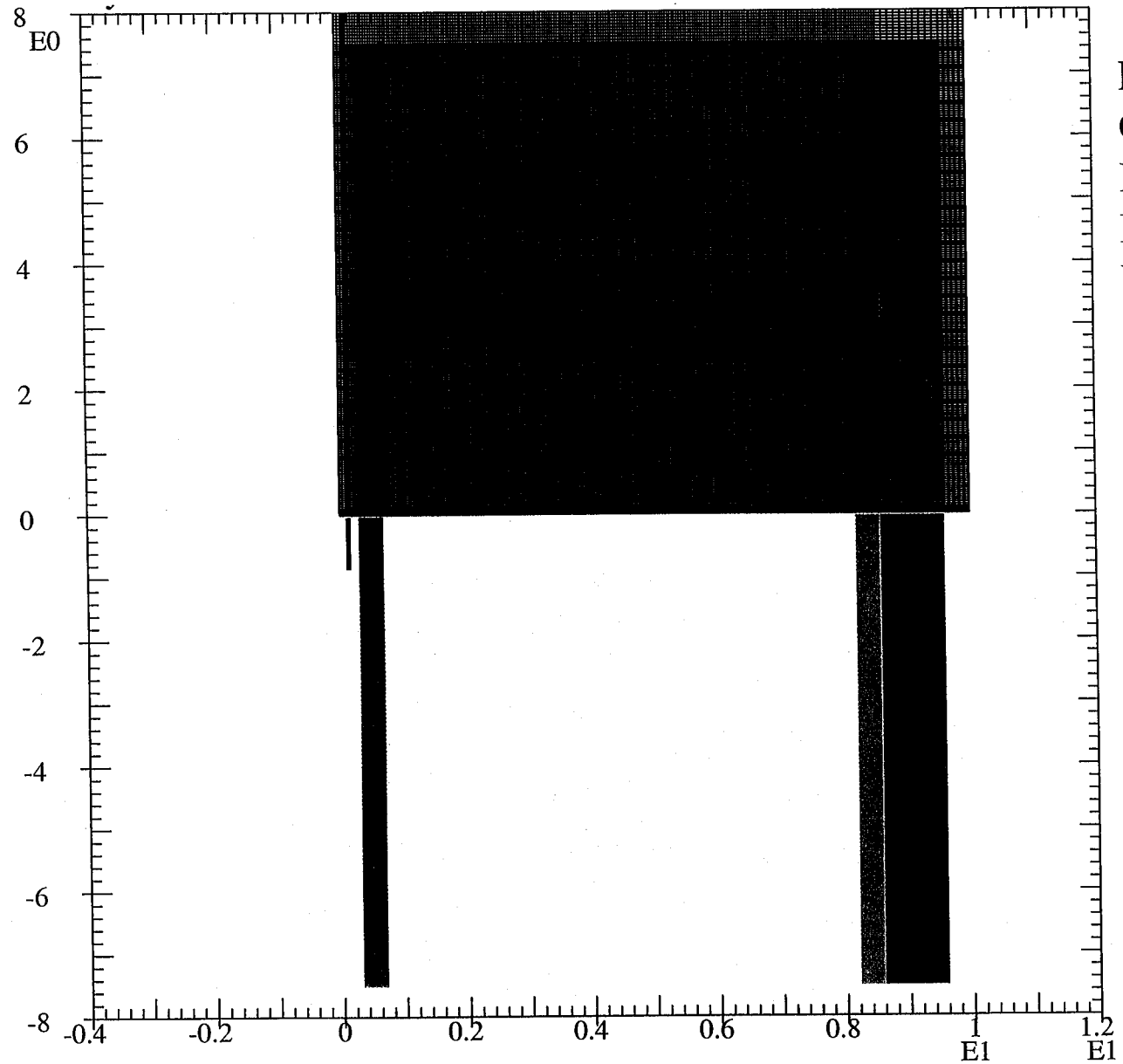


nmda--37-mg-7-2-2001

Figure 31

Second series NMD EOS experiments modeling calculations

Fine zoning (240x225) 17mm dia. proj. materials plot and zoning



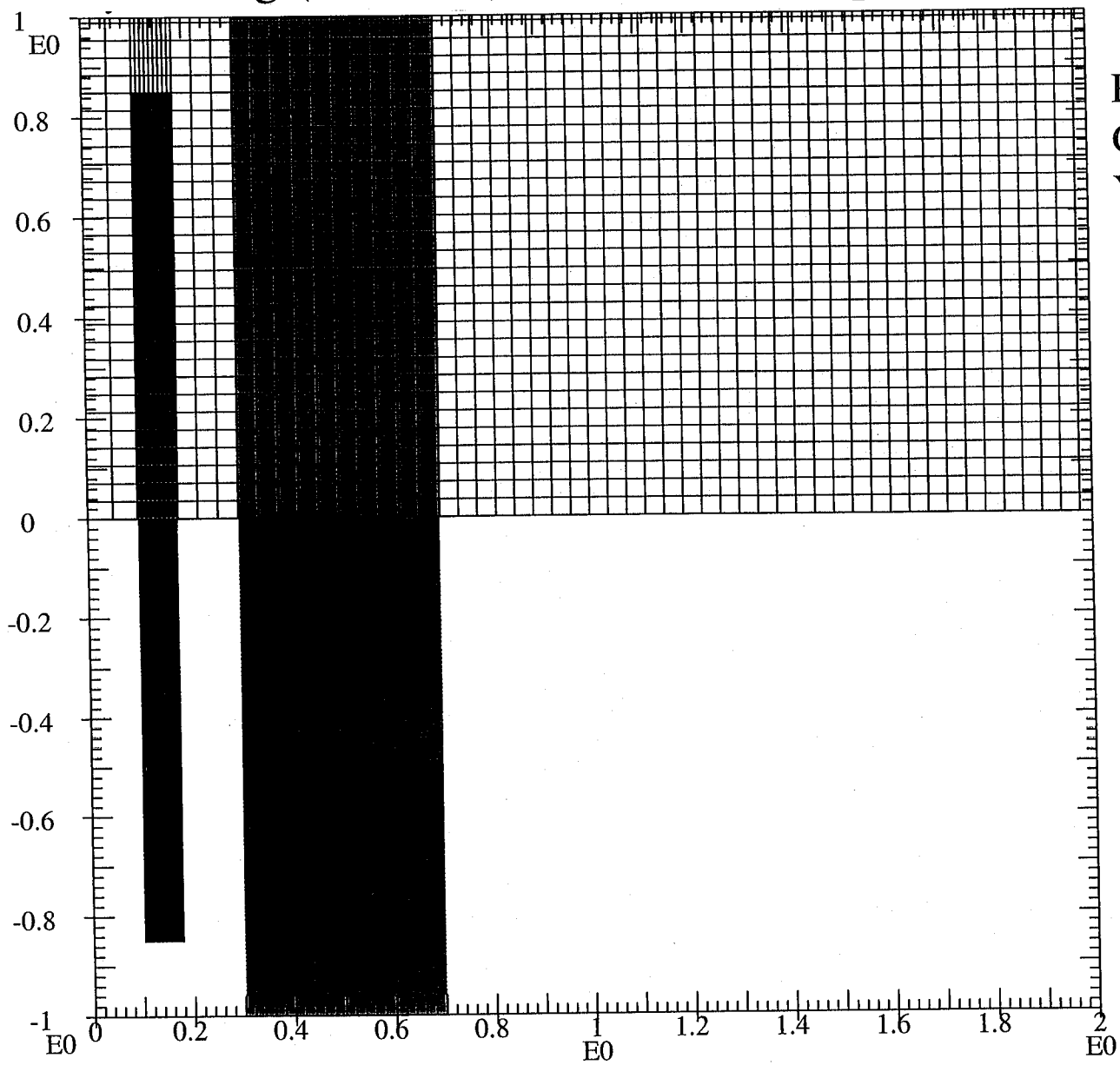
Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--21-mg-6-21-2001

Figure 32

Second series NMD EOS experiments modeling calculations

Fine zoning (240x225) 17mm diameter projectile closeup



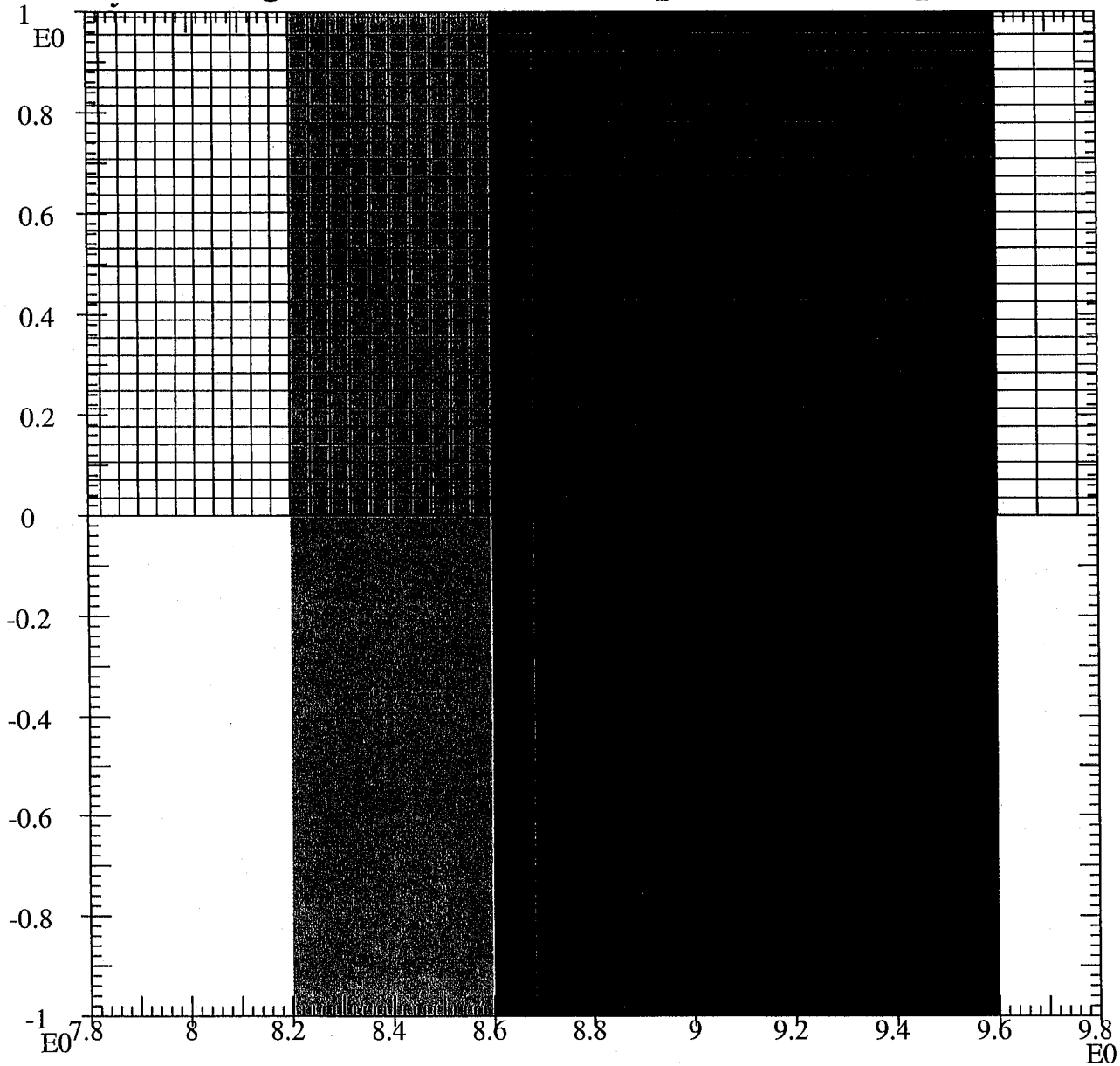
Red: projectile
Green: target
Yellow: vacuum background

nmda--22-mg-6-21-2001

Figure 33

Second series NMD EOS experiments modeling calculations

Fine zoning (240x225) closeup of witness plate and backing



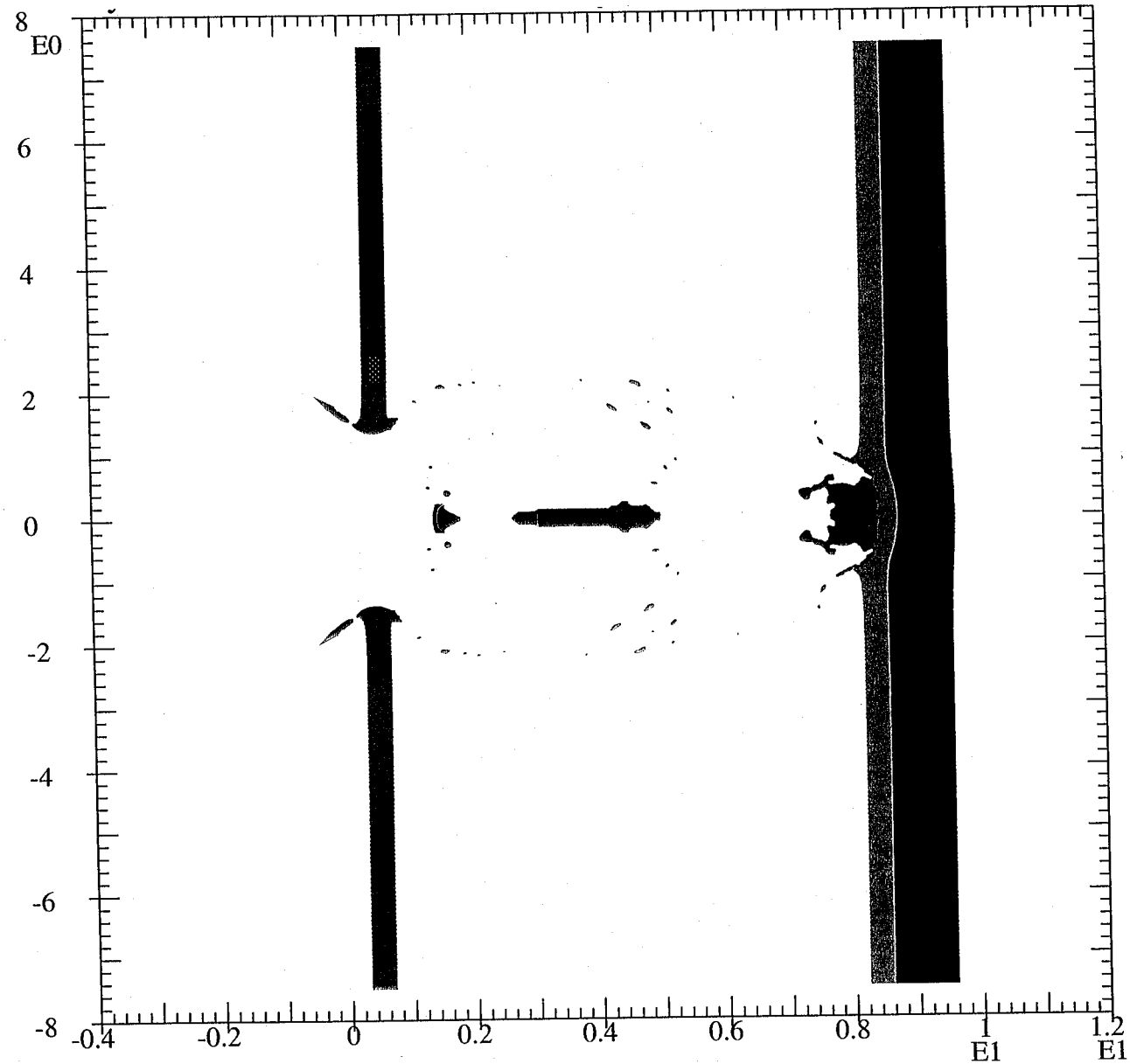
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

nmda--23-mg-6-21-2001

Figure 34

Second series NMD EOS experiments modeling calculations

Fine zoning (240x225) 17mm dia. proj. at 6km/s: t=20μs



Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

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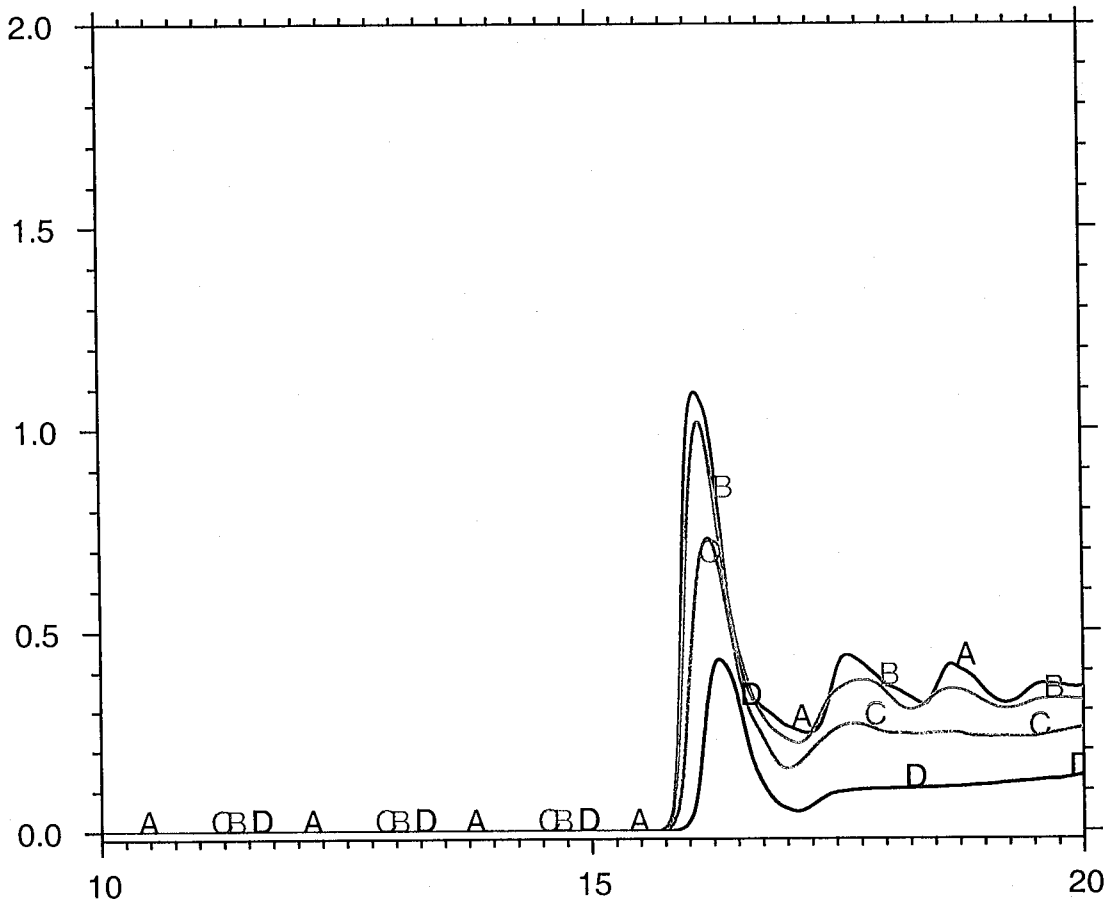
Figure 35

Second series NMD EOS experiments modeling calculations

Fine zoning (240x225) 17mm diameter projectile at 6km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away



Particle velocity (km/s)

Time (μs)

Figure 36

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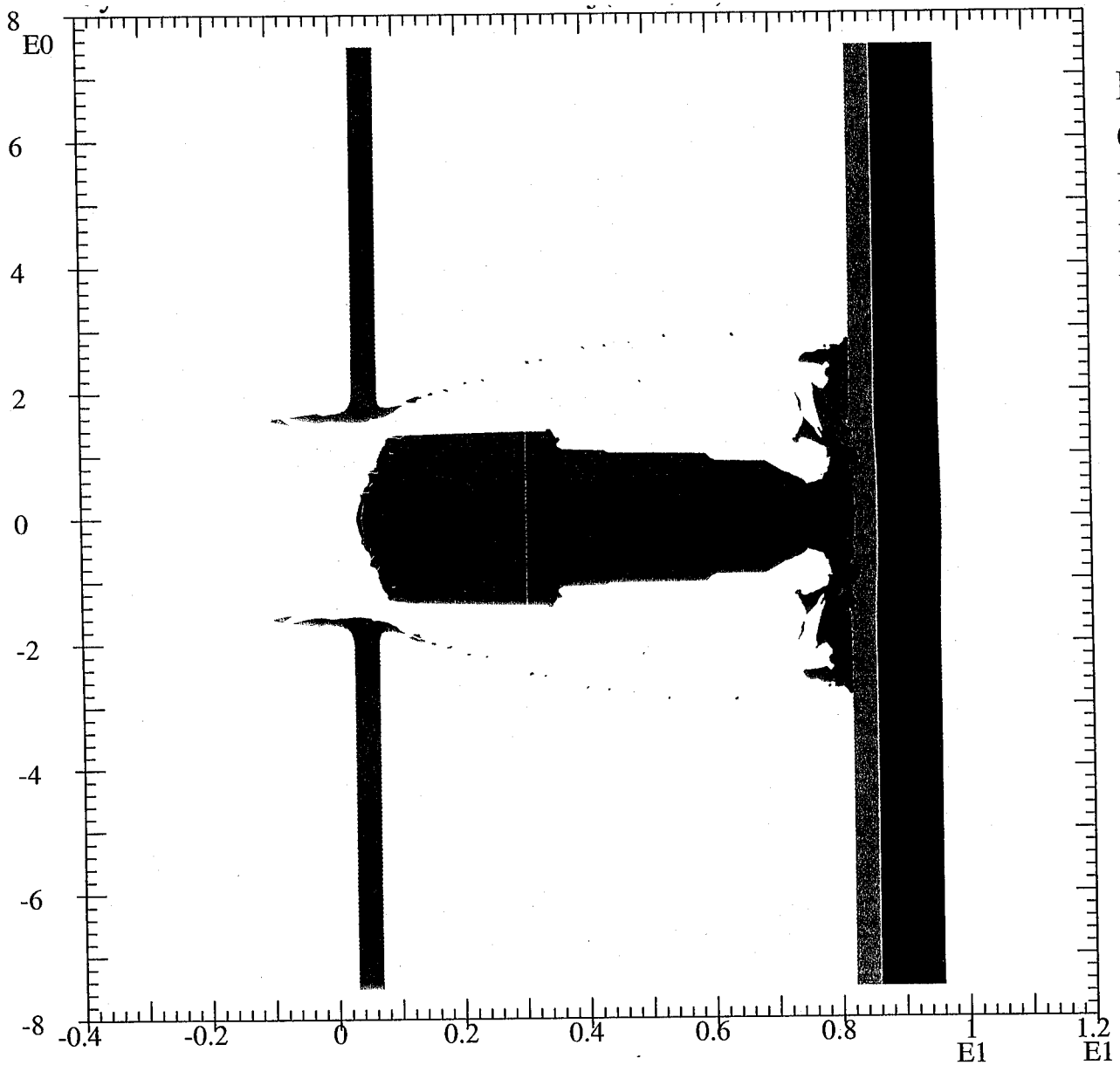
Second series NMD EOS experiments modeling calculations

Fine zoning (240x225) 17mm dia. proj. at 11km/s: t=10μs



Red: projectile
Green: target
Blue: witness plate
Dark blue: LiF
Yellow: vacuum background

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Figure 37

Second series NMD EOS experiments modeling calculations

Fine zoning (240x225) 17mm diameter projectile at 11km/s

Particle velocities at rear of witness plate on axis and 2,4 and 6mm away

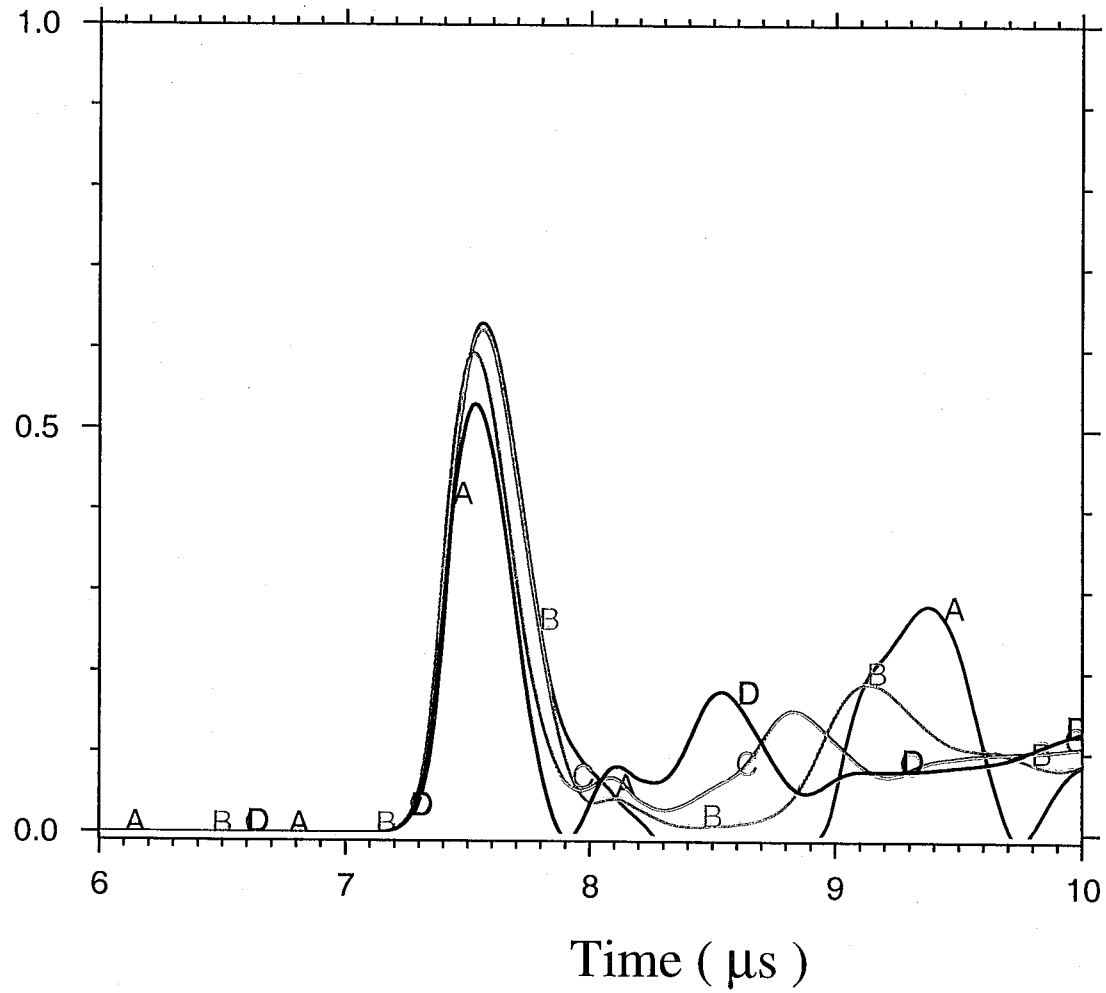

Figure 38

Second series NMD EOS experiments modeling calculations: little particle velocity profile dependence on zoning

17mm dia. projectile 6km/s particle velocity at rear of witness plate on axis

Red: 150x113 zones Blue: 240x225 zones

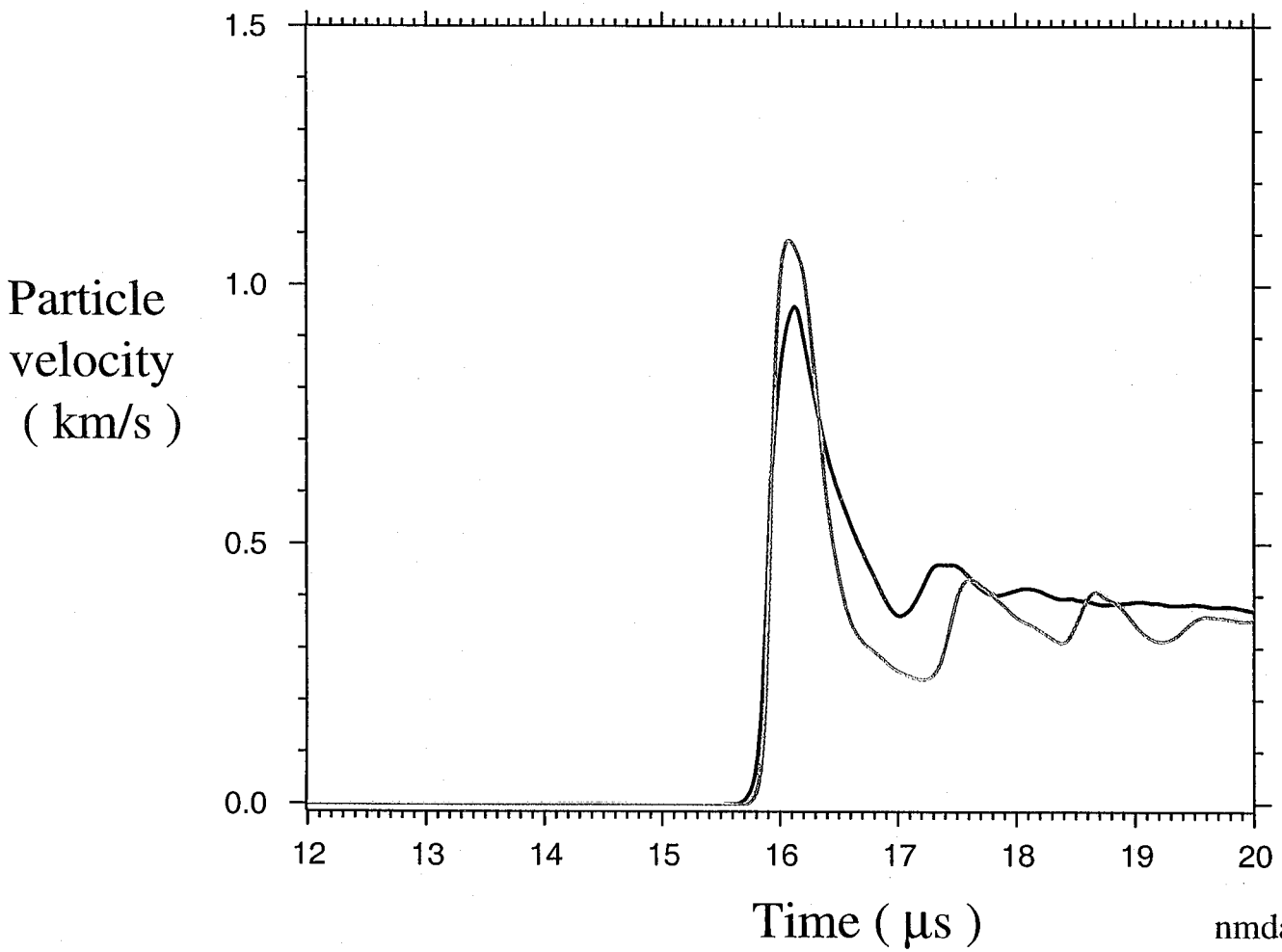

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Figure 39

Second series NMD EOS experiments modeling calculations: little particle velocity profile dependence on zoning

17mm dia. projectile 11km/s particle velocity at rear of witness plate on axis

Red: 150x113 zones Blue: 240x225 zones

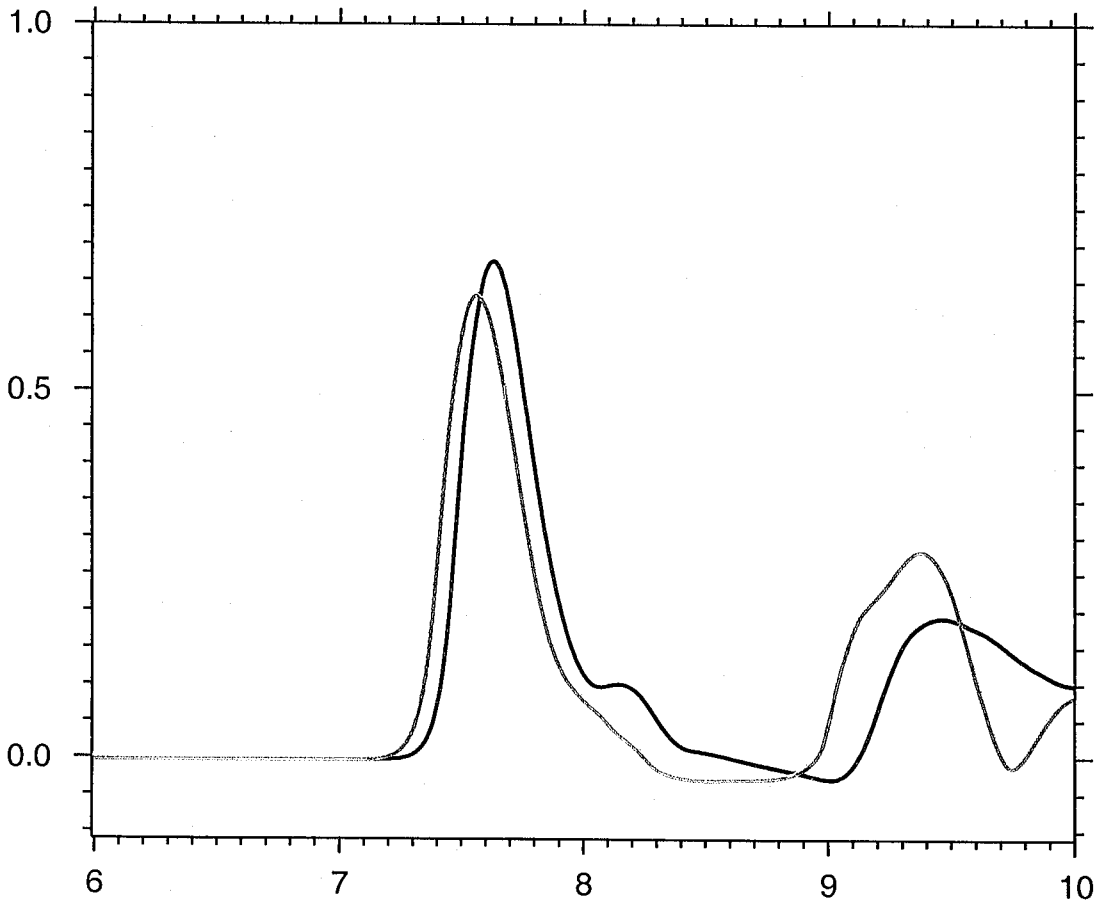

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Figure 40