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**MASTER**

**Observations of Plasma Tearing Instabilities  
and Associated Axial Translation in  
Field-Reversed Experiments**

University of California



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# Observations of Plasma Tearing Instabilities and Associated Axial Translation in Field-Reversed Experiments

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OBSERVATIONS OF PLASMA TEARING INSTABILITIES AND  
ASSOCIATED AXIAL TRANSLATION IN FIELD-REVERSED  
EXPERIMENTS

by

W. T. Armstrong, J. C. Cochrane, J. Lipson, M. Tuszewski

ABSTRACT

Tearing and reconnection processes during the formation and quiescent periods of a field-reversed configuration are studied with an axial array of compensated diamagnetic loops. Several representative plasma shots are documented.

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The formation of a field-reversed configuration (FRC) includes the resistive tearing and reconnection of oppositely directed field lines at the ends of a hot plasma produced in a theta-pinch.<sup>1,2</sup> A single, closed-field-line FRC is obtained, which typically persists in a quiescent, equilibrium state for up to 50  $\mu$ s before a rotational instability disrupts the configuration. Various past work indicates that further tearing during the quiescent phase may occur and result in multiple FRC cells.<sup>3,4,5</sup> Experiments on the FRX-B field-reversed theta-pinch have typically not shown such tearing phenomena at later times.<sup>1</sup> However, recent experiments on FRX-B at higher fields and higher densities have indicated that tearing effects appear on ~30% of the shots. The characteristics of these tearing modes vary greatly from shot to shot. The tearing rate may be controlled by local resistivity changes due to variation in impurity distributions, pre-ionization conditions or anomalous turbulence levels. The tearing rate may be further affected by plasma flow. Because there are so many contributing factors to the tearing rate, it is extremely difficult to quantify the tearing behavior under the present experimental controls. Hence, this report is intended to simply document representative plasma shots which display the diversity of the observed tearing behavior.

The experimental conditions are as follows:

|             |               |
|-------------|---------------|
| Coil i.d.   | 25 cm         |
| Coil length | 100 cm        |
| End-mirrors | 10% in vacuum |

|                   |                               |
|-------------------|-------------------------------|
| Fill gas          | 29 to 49 mtorr D <sub>2</sub> |
| B <sub>bias</sub> | -3.0 kG                       |
| B <sup>max</sup>  | +13.0 kG                      |
| B(t = 10 μs)      | ~10.0 kG                      |
| τ <sub>I/4</sub>  | ~2.6 μs                       |
| τ <sub>L/R</sub>  | ~120 μs.                      |

where τ<sub>I/4</sub> is the quarter period rise time of the main field. The principal diagnostic is an axial array of nine compensated diamagnetic loops. This diagnostic provides an axial profile of the effective diamagnetic radius, or excluded flux radius, defined by

$$r_{\Delta\phi} = r_{\ell} \left( 1 - \frac{\int_{\ell} B dA}{\pi r_{\ell}^2 B_0} \right)^{1/2},$$

where r<sub>ℓ</sub> is the radius of the conducting loop measuring the enclosed flux ∫<sub>ℓ</sub> B dA and B<sub>0</sub> is the external field measured at r<sub>ℓ</sub>. In the present study a single loop measuring the enclosed flux was used. The loop was positioned in the coil midplane just inside the coil. Since the coil surface approximates a flux surface to a high accuracy, a single loop suffices. The nine probes along the axis measuring the local B<sub>0</sub> are balanced with the loop on a vacuum shot to calibrate differences in sensitivity and phase. The diagnostic data presented here includes:

|   |              |
|---|--------------|
| r <sub>Δφ</sub> axial profiles                          | vs t         |
| r <sub>Δφ</sub> at each station                         | vs t         |
| B <sub>0</sub> in the midplane                          | vs t         |
| T <sub>i</sub> from CV 2271Å Doppler broadening         | vs t         |
| CV 2271Å total intensity (I)                            | vs t         |
| T <sub>i</sub> from gaussian fit<br>of CV 2271Å profile | at t = 10 μs |
| Intensity of CV 2271Å in channels<br>separated by ~.3Å. | vs t         |

The  $r_{\Delta\phi}$  axial profiles display the gross plasma changes due to tearing and axial translation which are of present interest. The history of  $T_i$  is a good indicator of the lifetime of the closed-field-line FRC. Whereas, the individual channel signals of CV 2271Å radiation clearly show the onset of the rotational instability in the appearance of a modulation of the signal amplitude.

Tearing is associated with other plasma behavior found in the following data. In particular, axial translation of the FRC sometimes occurs. Translation may in some instances be due to nonsymmetric field reconnection during FRC formation or due to additional tearing at later times.

There are seven shots presented displaying the following behavior:

- 1) no translation, or tearing (typical of 70% of the shots taken)
- 2) early rapid translation
- 3) later translation
- 4) tearing into two FRC's with each FRC persisting
- 5) tearing into two FRC's which coalesce
- 6) tearing into two FRC's with one possibly translating out of the coil
- 7) early translation with later tearing and total disruption of the FRC.

Each shot is characterized by the following information:

shot #  
fill pressure  $P_0$   
time at which main field was initiated  
tearing and translation behavior  
stable period  $\tau_s$  (to the onset of the rotational instability)  
lifetime (to the disruption of the FRC).

Otherwise, the data is presented without further interpretation.

Case #1

Shot #3016

$P_o = 29$  mtorr

$\tau_o = 20.0$   $\mu$ s

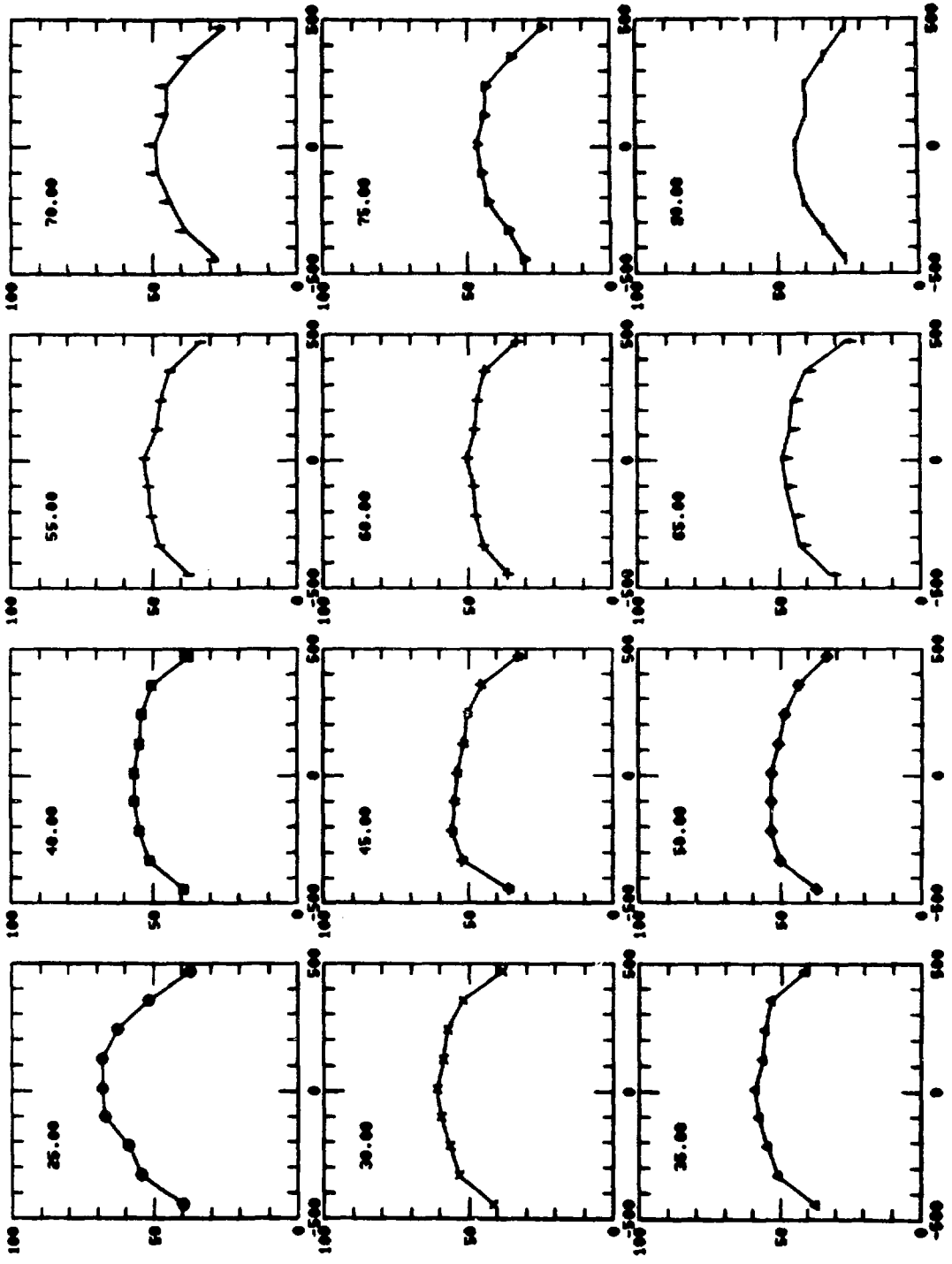
no translation or tearing

$\tau_s \approx 42$   $\mu$ s

$\tau_l \approx 80$   $\mu$ s

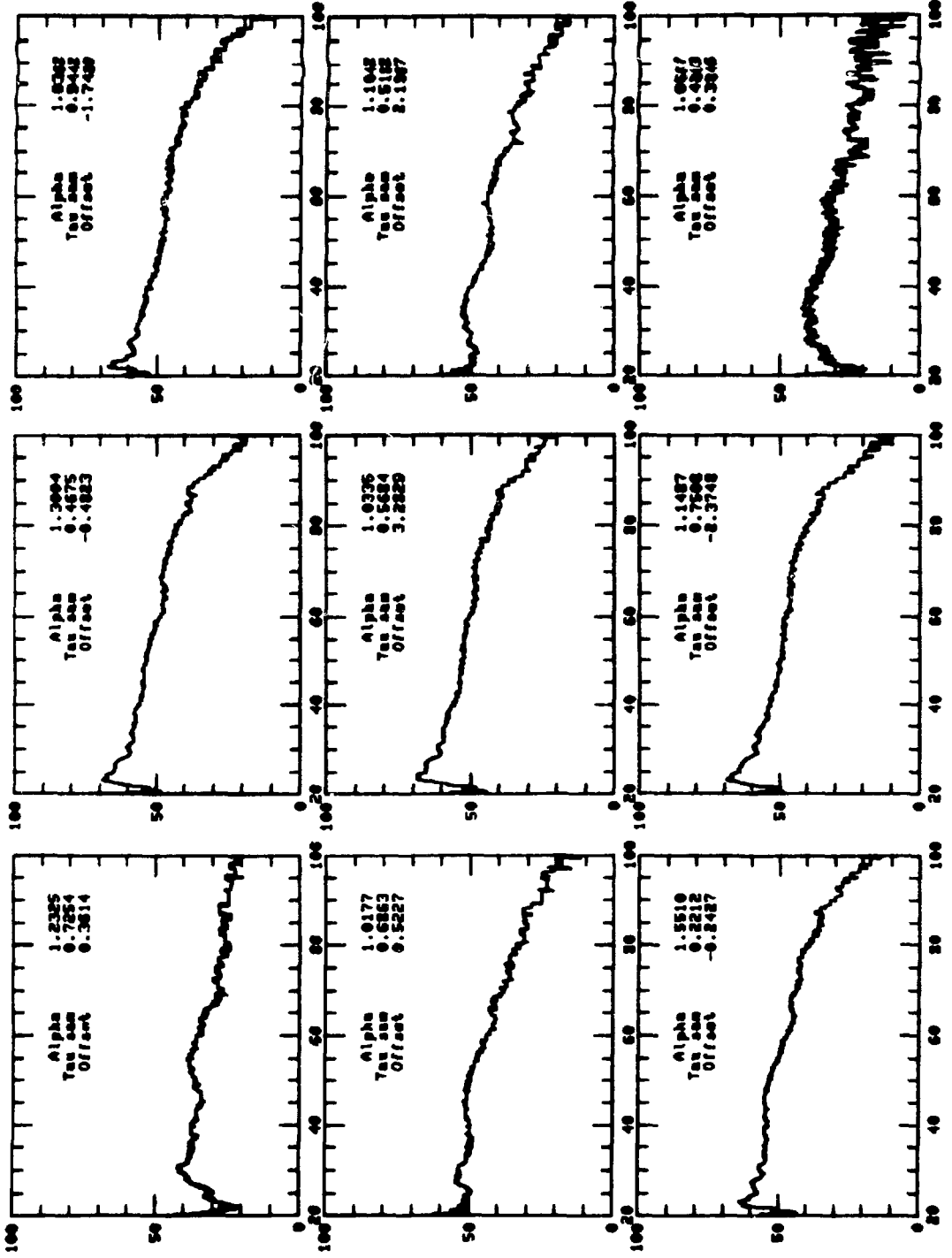
(typical of ~70% of the shots taken)

FR Shot 3016 Type 2 4000 Scherr 10/23/80 1426 Radius



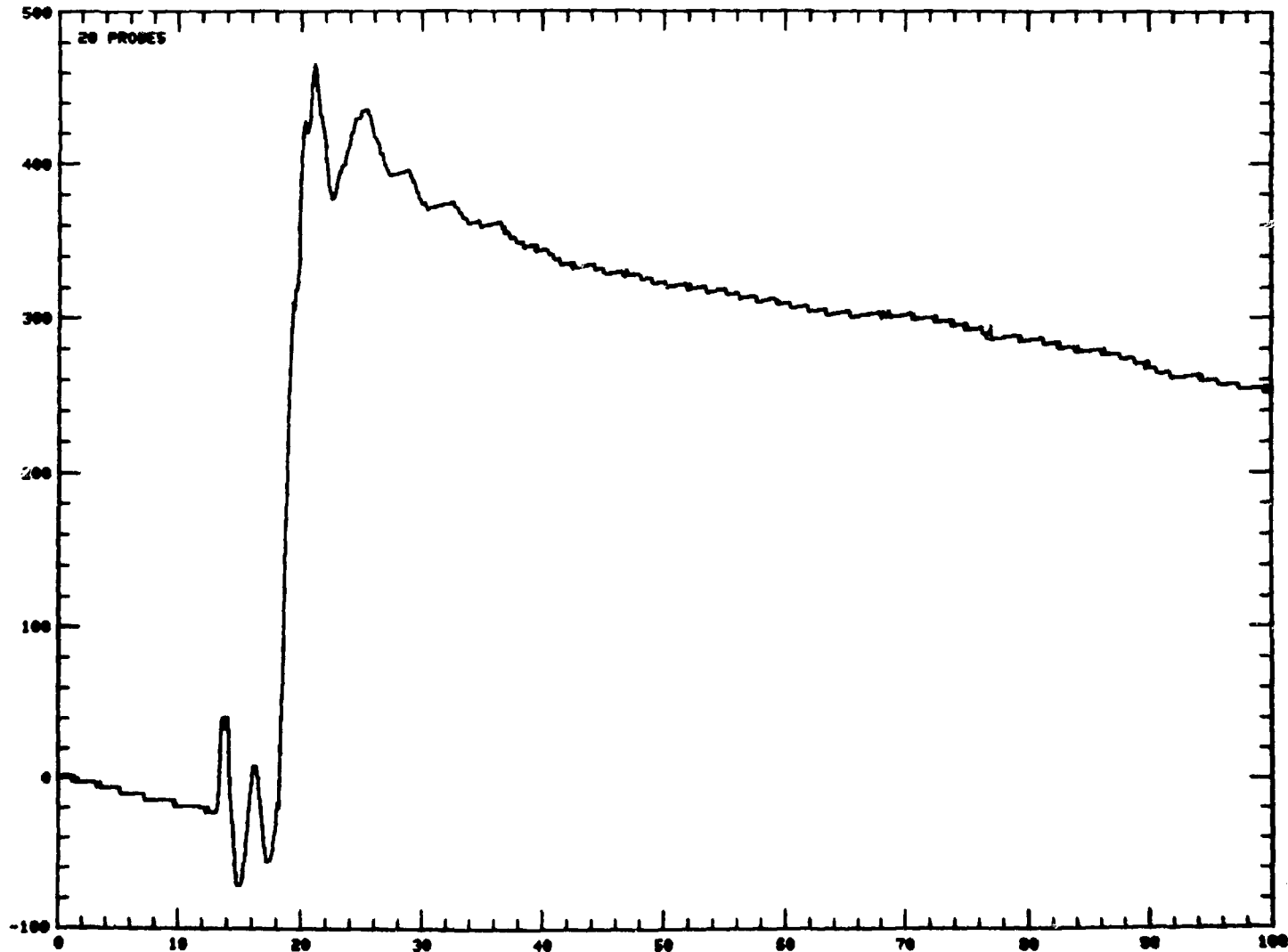
$R_{\Delta\phi}$  (mm) vs  $z$  (mm) and  $t$  ( $\mu s$ )

FR Shot 3016 Type 2 4000 2Shoterr 10/23/99 1426 Radius



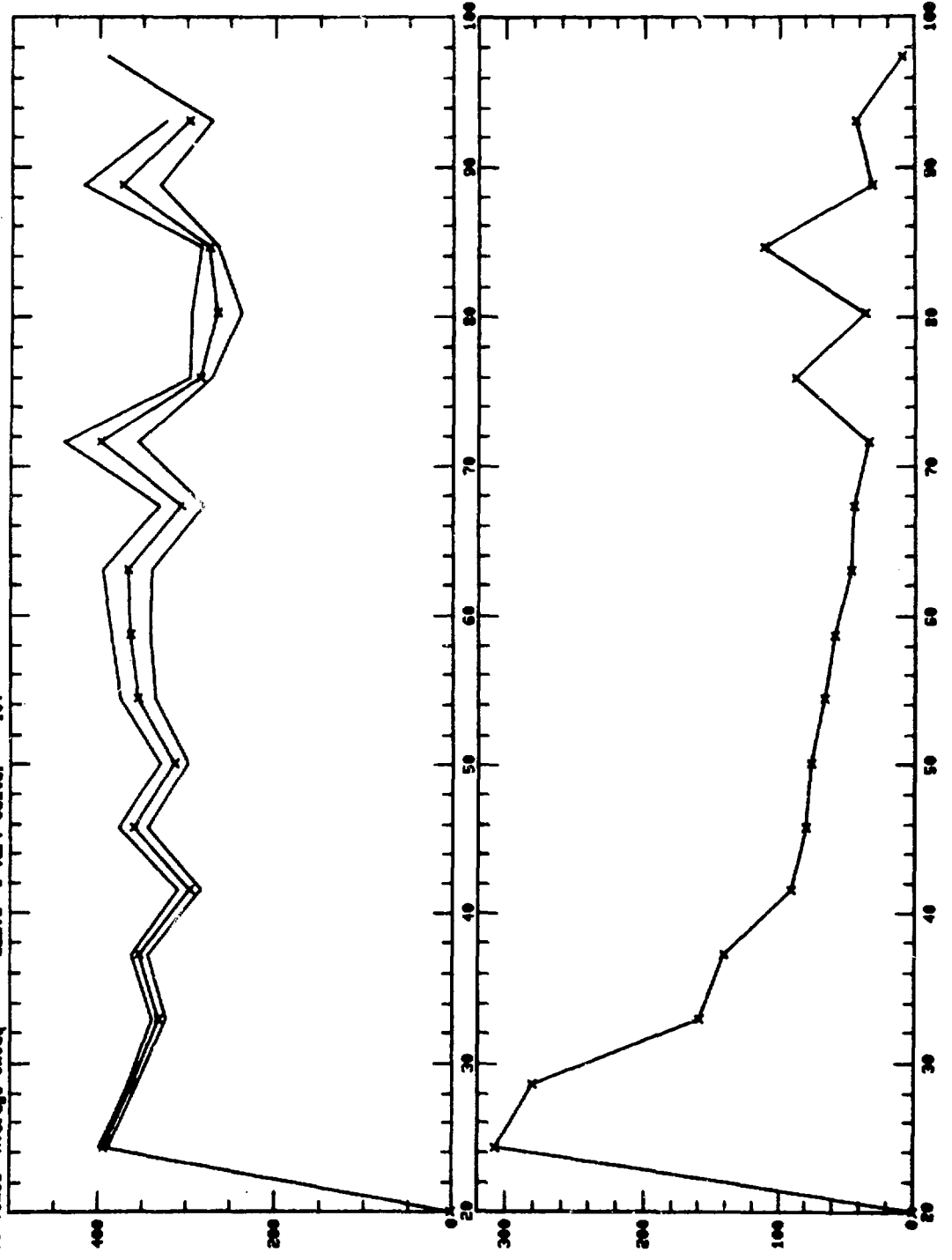
$r_{\alpha}$  vs  $L$ (mm) and  $z$ (mm)





$B_0$  (arbitrary units) vs  $t$  ( $\mu$ s) at  $z = 0$

Shot 3015 Type 2 400V 20-terr 10/23/80 1426  
 Bepler Temperature Coostat 200.0uV -10.0mV  
 19 Times Average Chisq 222.3 3 Var. Center -10.

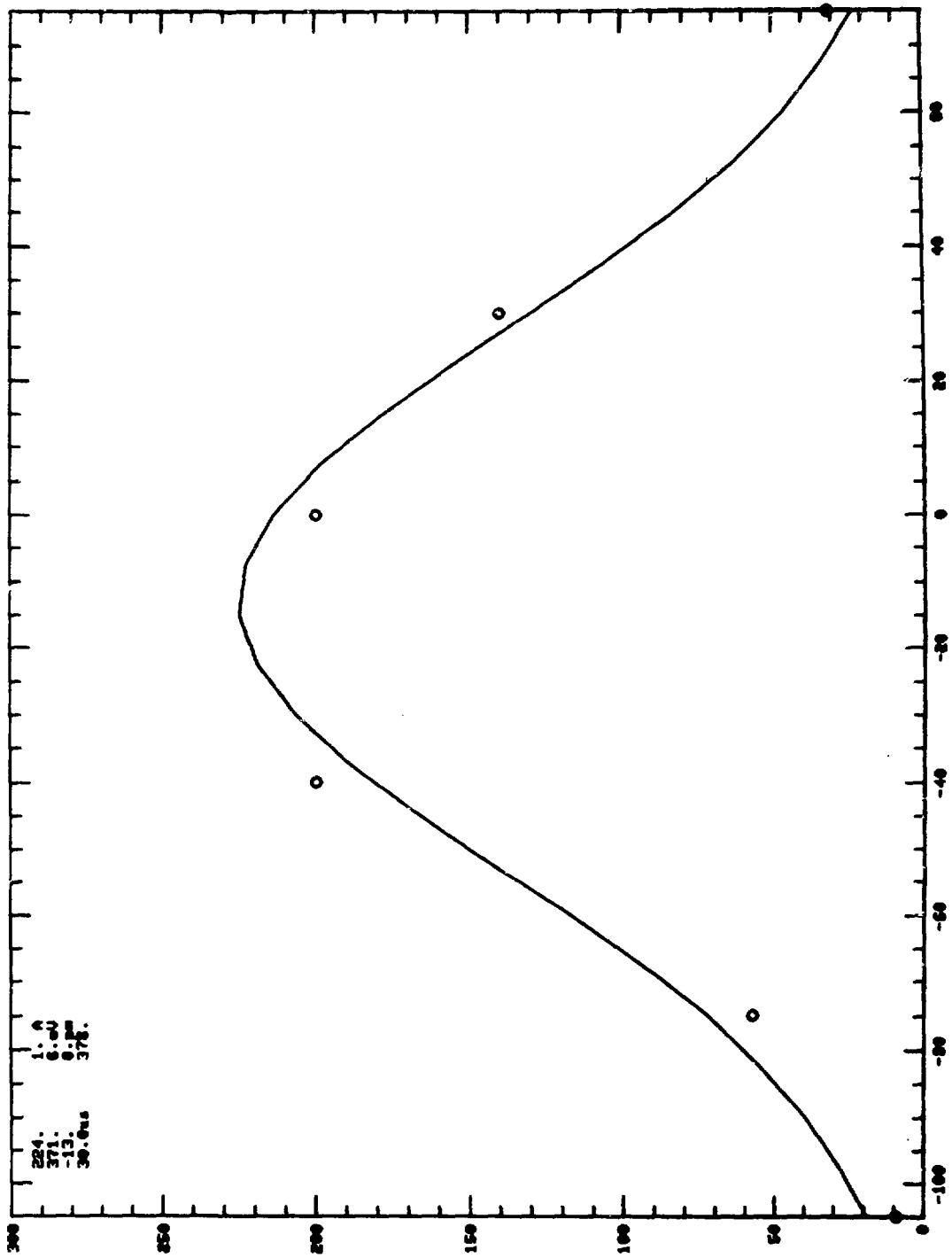


$T_i$  (eV) vs  $t$  ( $\mu s$ ) and  $I$  (arbitrary units) vs  $t$  ( $\mu s$ )

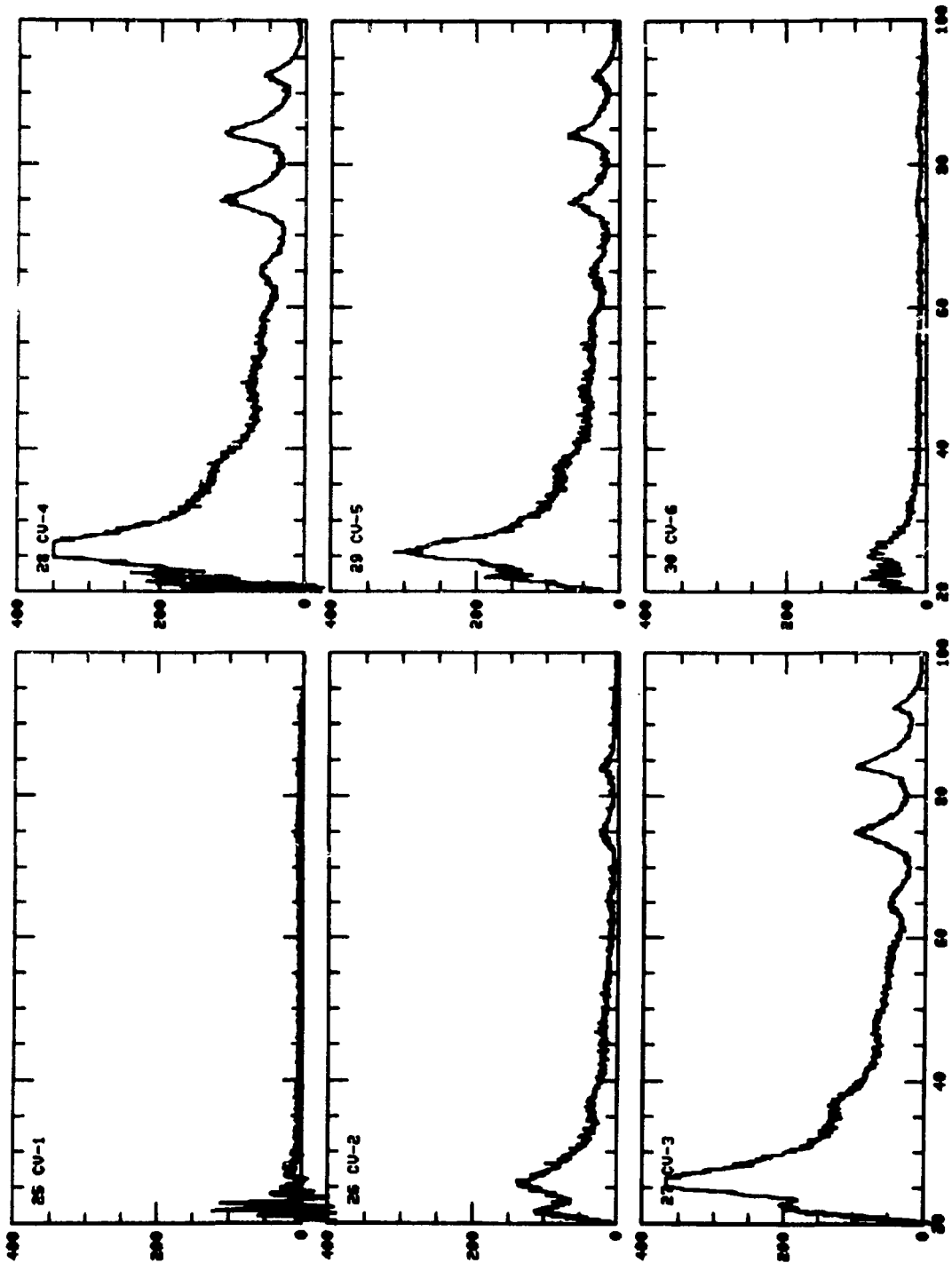
Shot 3016 Type 2 400V 29morr 10/23/80 1426  
Doppler Temperature Guess! 200.0eU -10.0ys

224.  
371.  
-13.  
30.6us

1. A  
6.0U  
0.8pm  
378.



$I(\Delta\lambda)$  (arbitrary units) vs  $\Delta\lambda$  (pm) at  $t = 10 \mu s$



$I$  in each CV channel vs  $t$  ( $\mu s$ )

Case #2

Shot #3013

$$P_o = 29 \text{ mtorr}$$

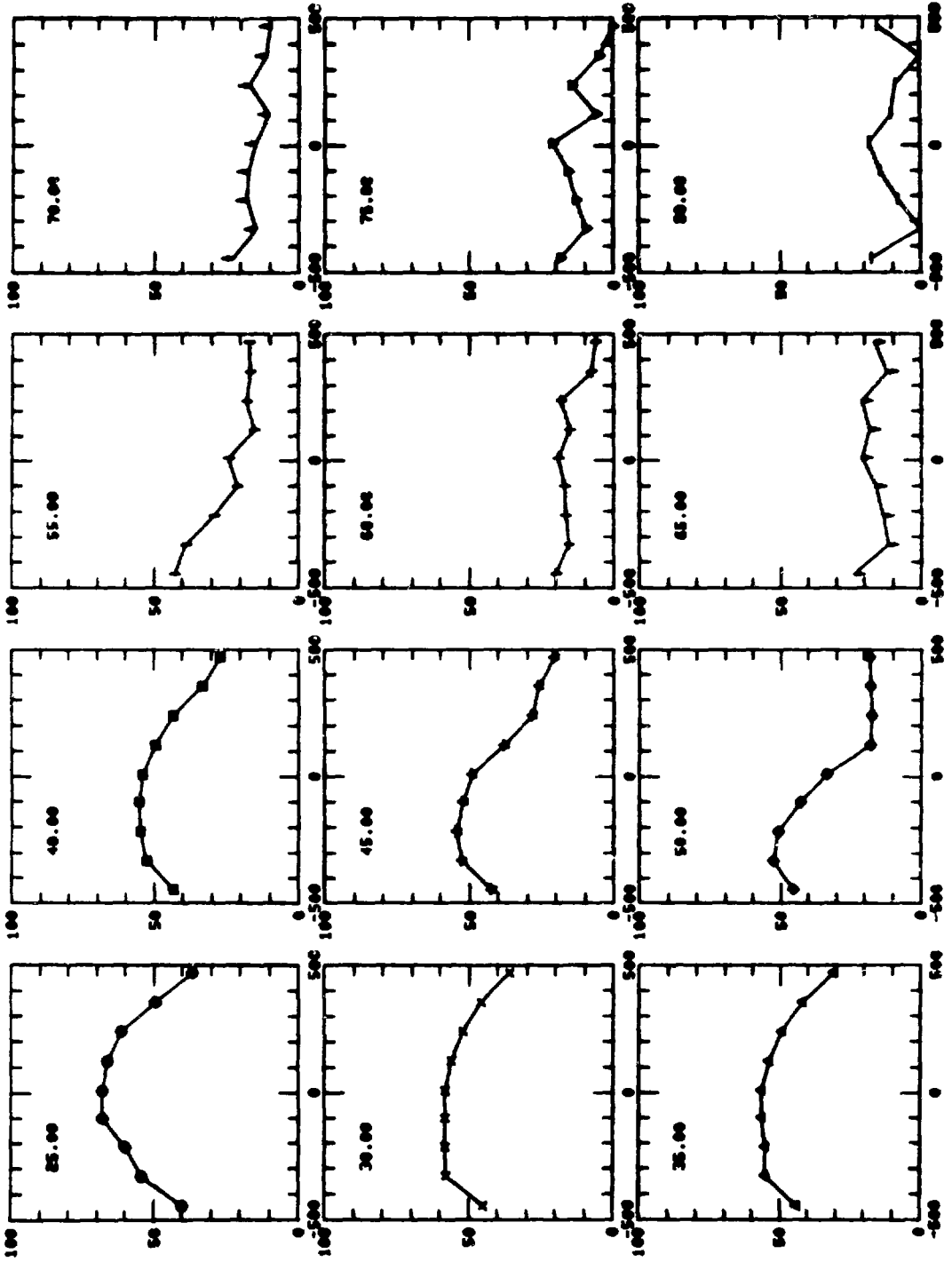
$$t_o = 20.0 \text{ } \mu\text{s}$$

rapid translation left at  $t_o + 20 \text{ } \mu\text{s}$  destroying FRC

$$\tau_s = ? \text{ (rotational instability not observed)}$$

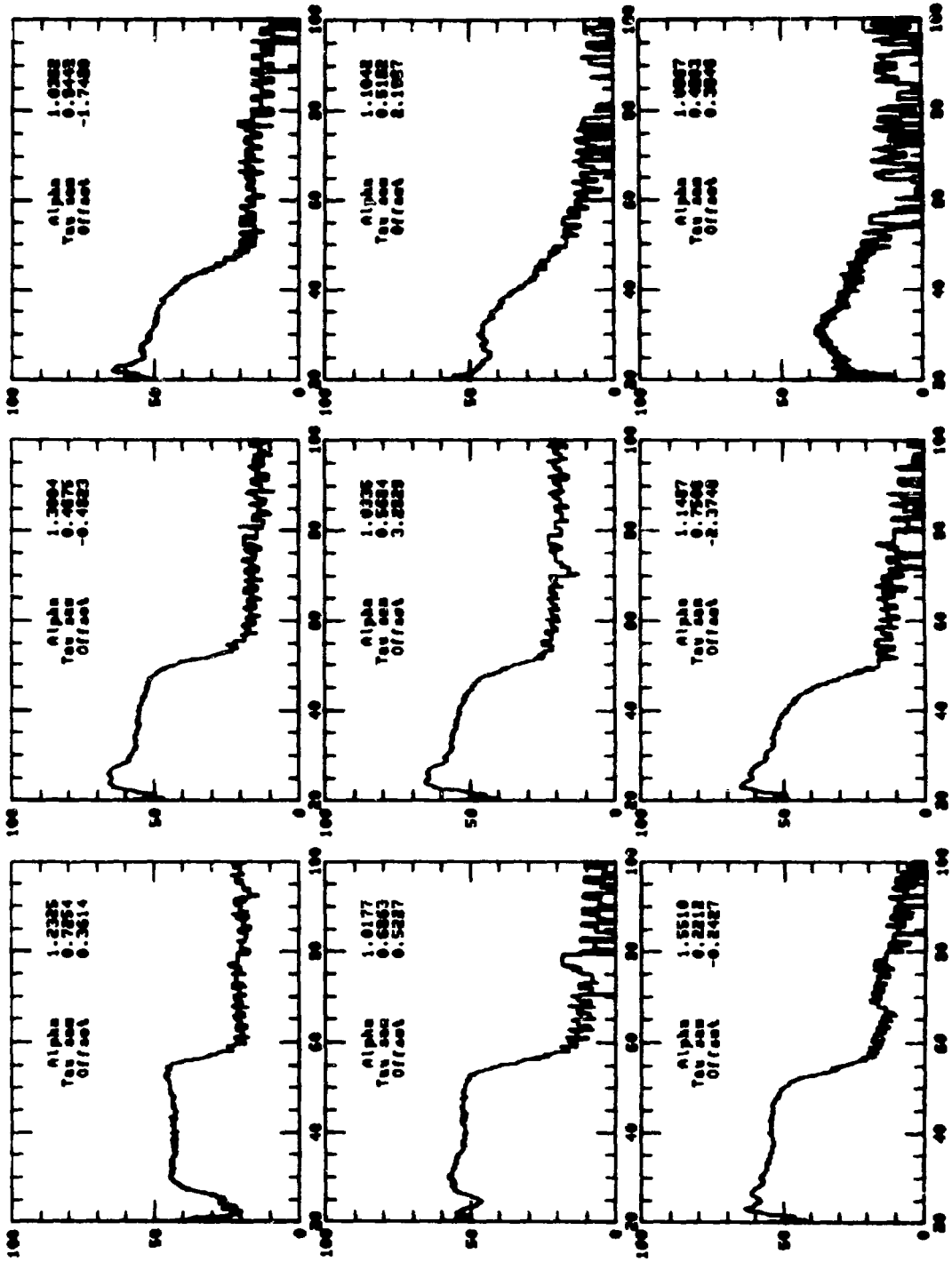
$$\tau_d \approx 27 \text{ } \mu\text{s}$$

FR Shot 3013 Type 2 4000 20merr 10/23/80 1413 Radius



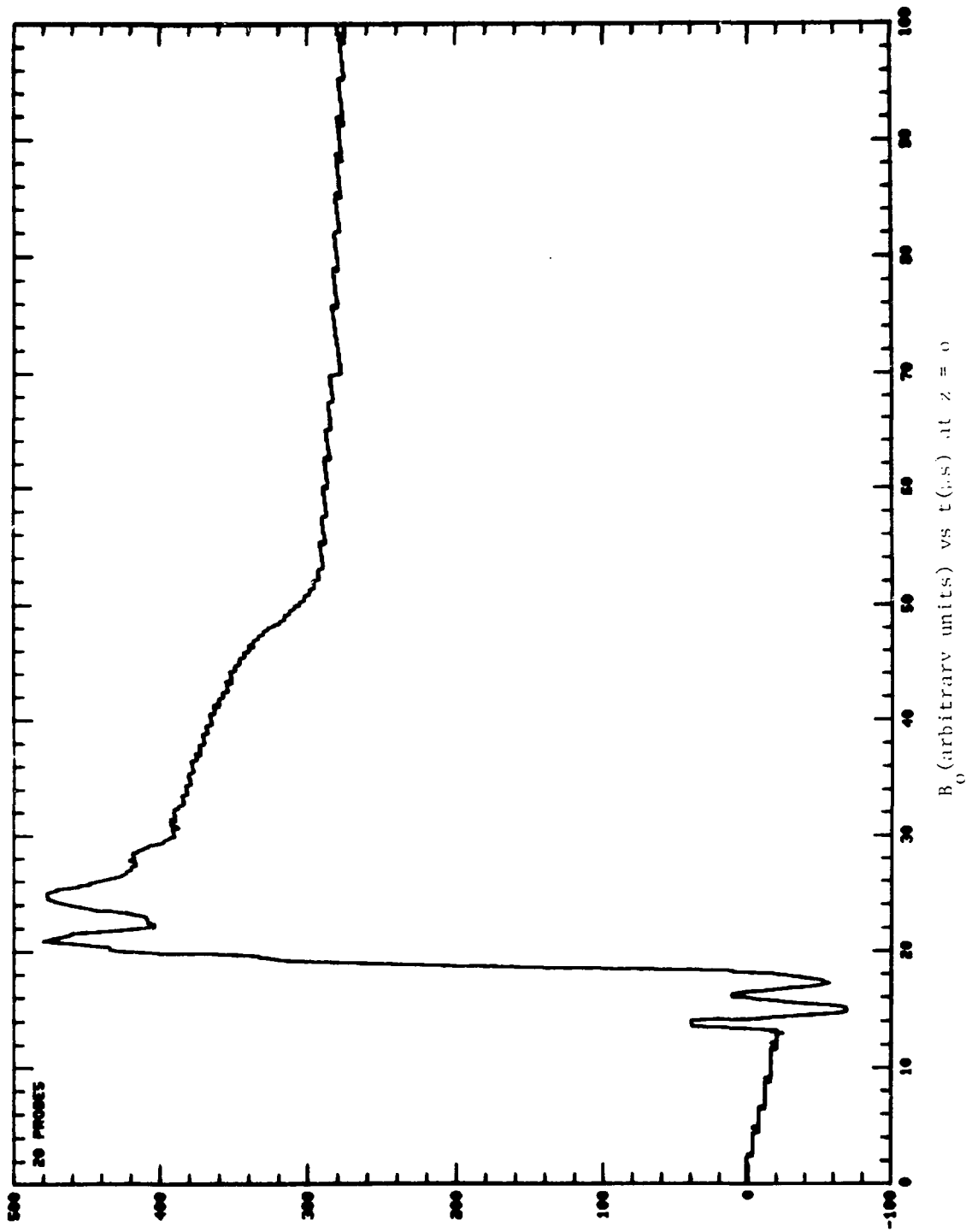
$r_{\Delta\phi}$  (nm) vs  $z$  (mm) and  $t$  ( $\mu s$ )

FR Shot 3013 Type 2 400U 25enterr 10/23/80 1413 Radius



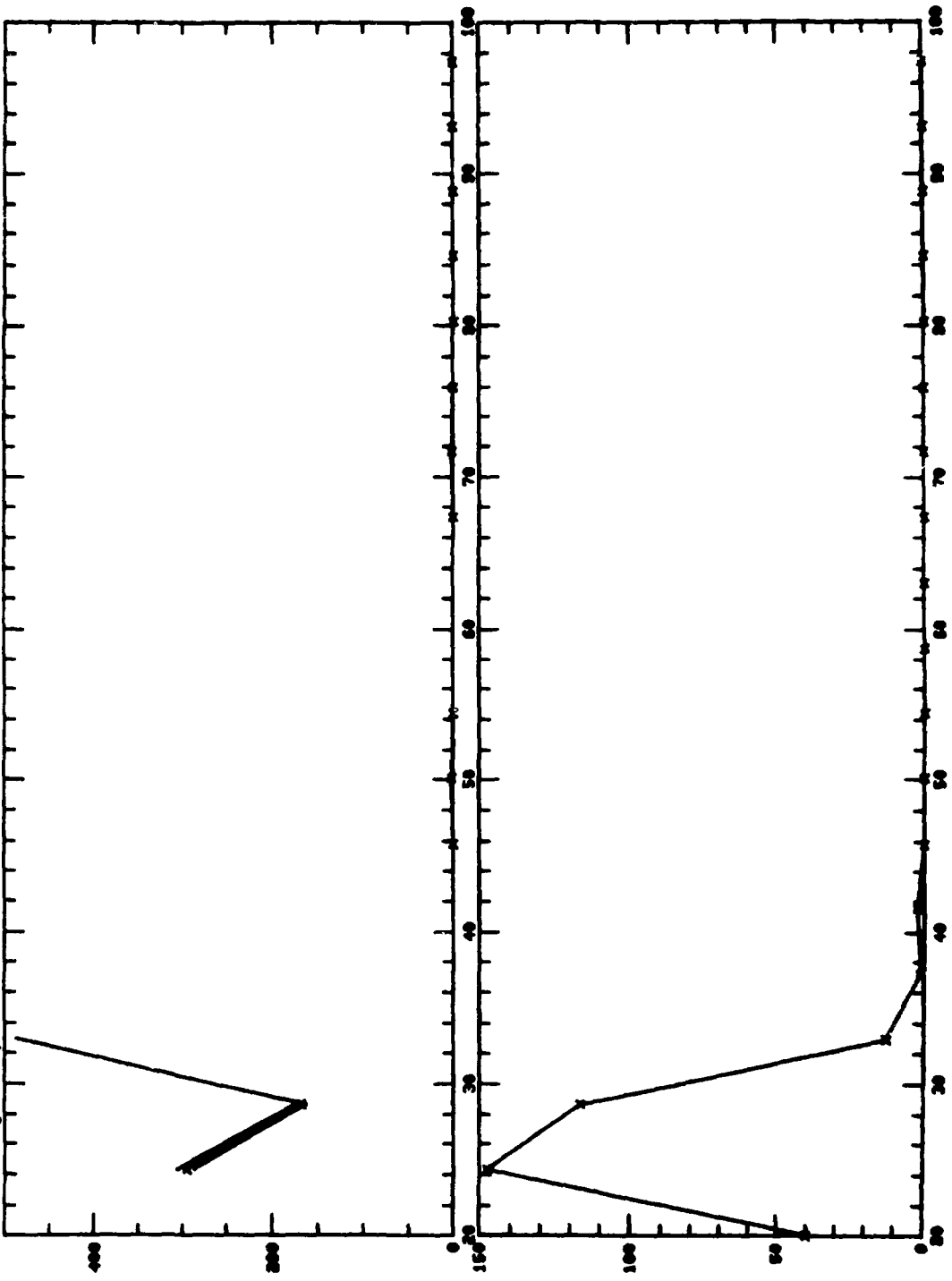
$R_z$  (mm) vs  $L$  (cm) and  $Z$  (mm)

FR Shot 3013 Type 2 4000 20beterr 10/23/88 1413 Normalis



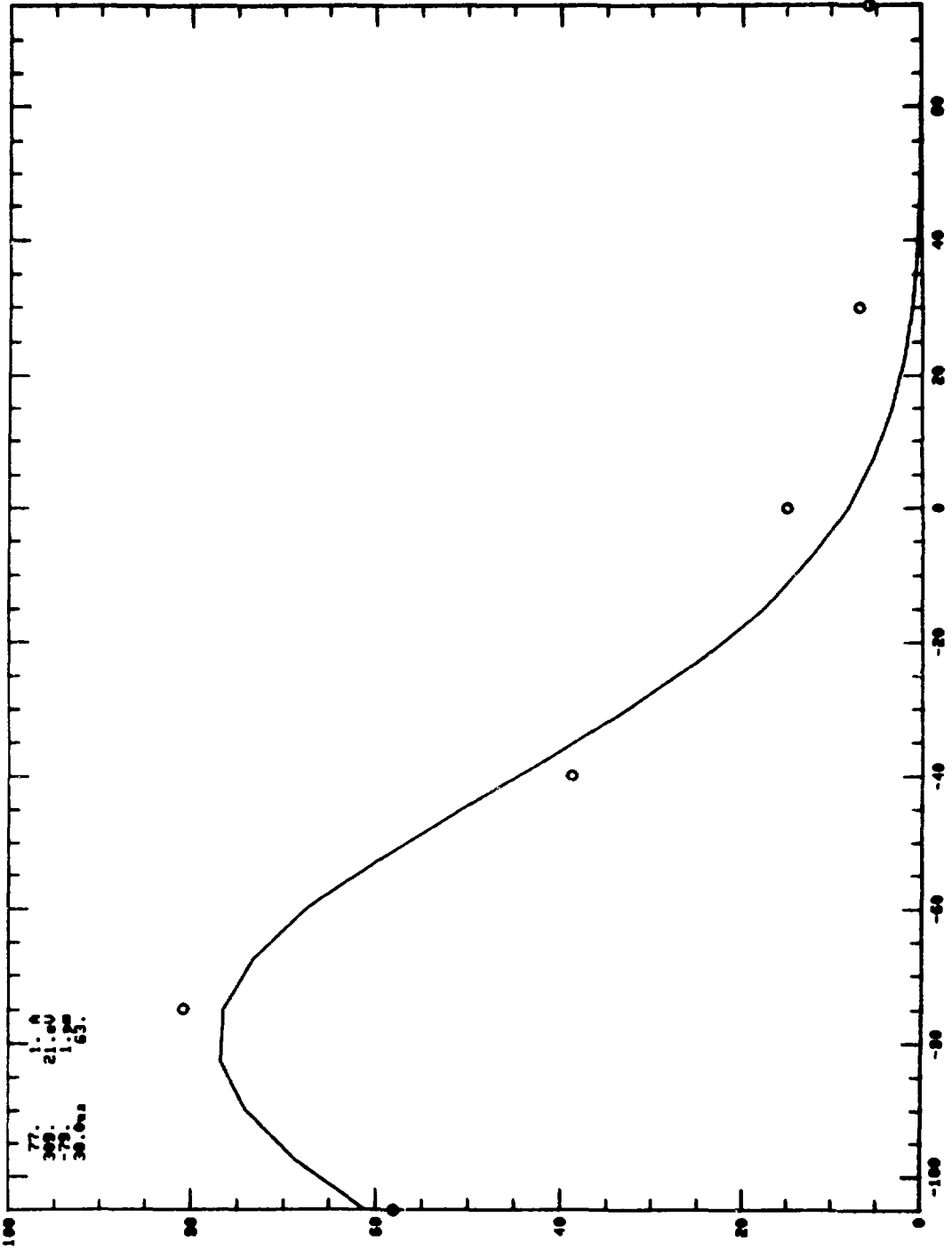


Shot 3013 Type 2 400U 200torr 10/23/80 1413  
 Boppler Temperature Constant 200.0eV -10.0ps  
 10 Times Average Chiq 743.2 3 Var. Center -10.

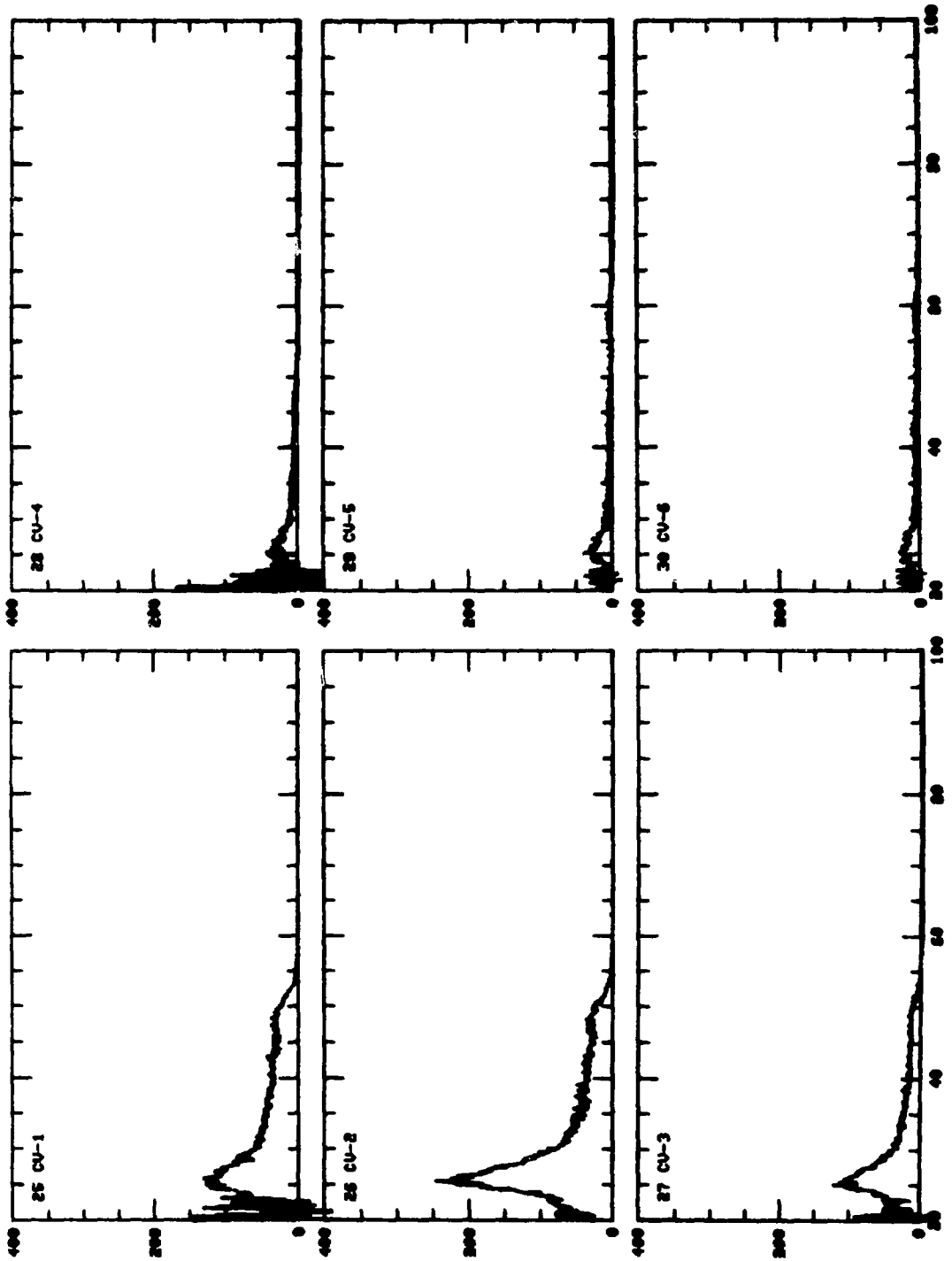


T<sub>j</sub> (eV) vs t (μs) and T (arbitrary units) vs t (μs)

Shot 3013 Type 2 400U 20merr 10/23/00 1413  
Doppler Temperature Guess 200.0au -10.0pm



FR Shot 3013 Type 2 400U 20cterr 10/23/00 1413 Normalis



I in each CV channel vs t ( $\mu\text{s}$ )

Case #3

Shot #3007

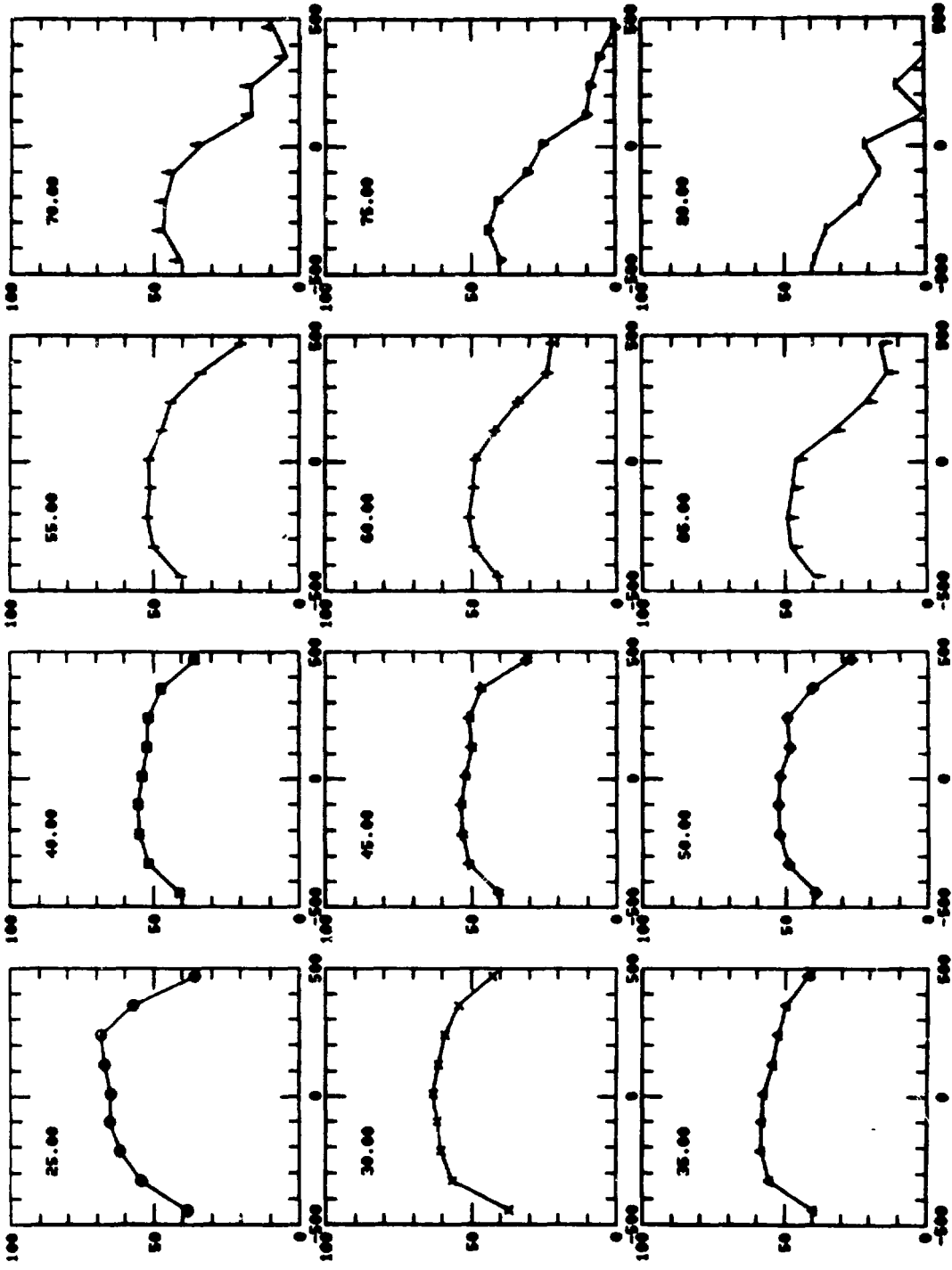
$P_o = 29$  mtorr

$t_o = 20.0$   $\mu$ s

delayed translation left at  $t_o + 35$   $\mu$ s destroying FRC

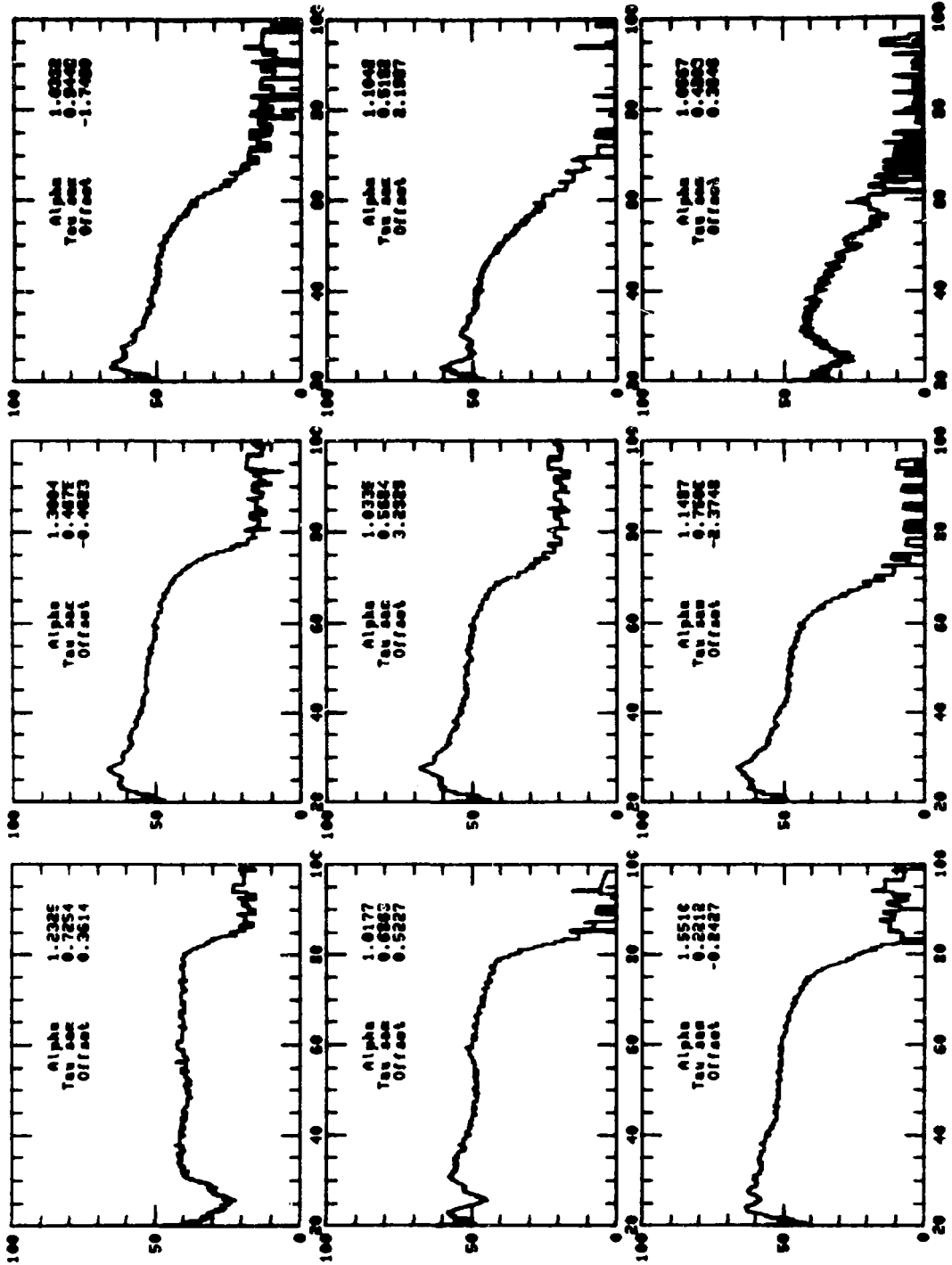
$\tau_s = ?$  (rotational instability not observed)

$\tau_g \approx 50$   $\mu$ s



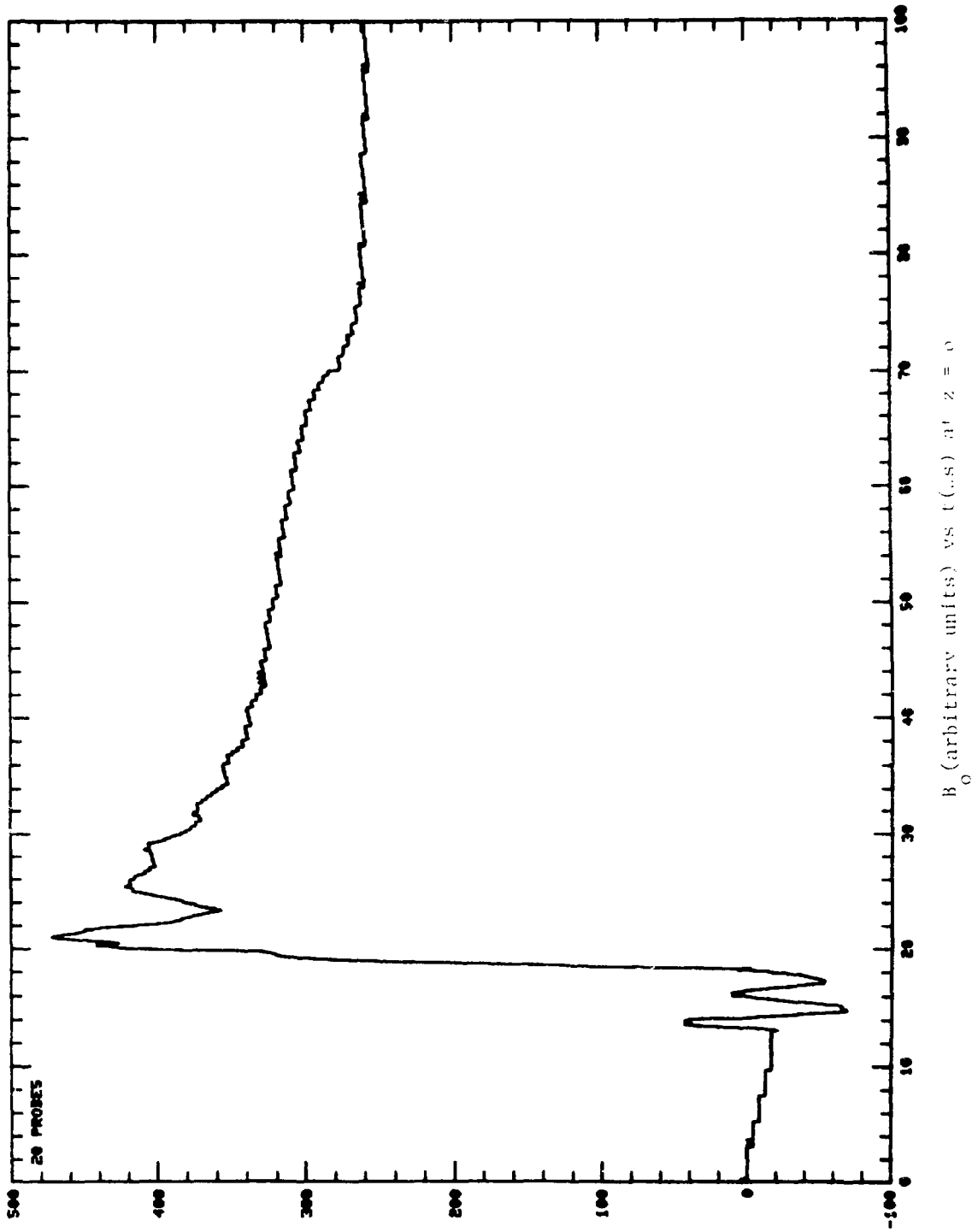
$R_{\Delta\phi}$  (mm) vs  $z$  (mm) and  $t$  ( $\mu s$ )

FR Shot 3007 Type 2 400V 29mlorr 10/23/80 1142 Radius

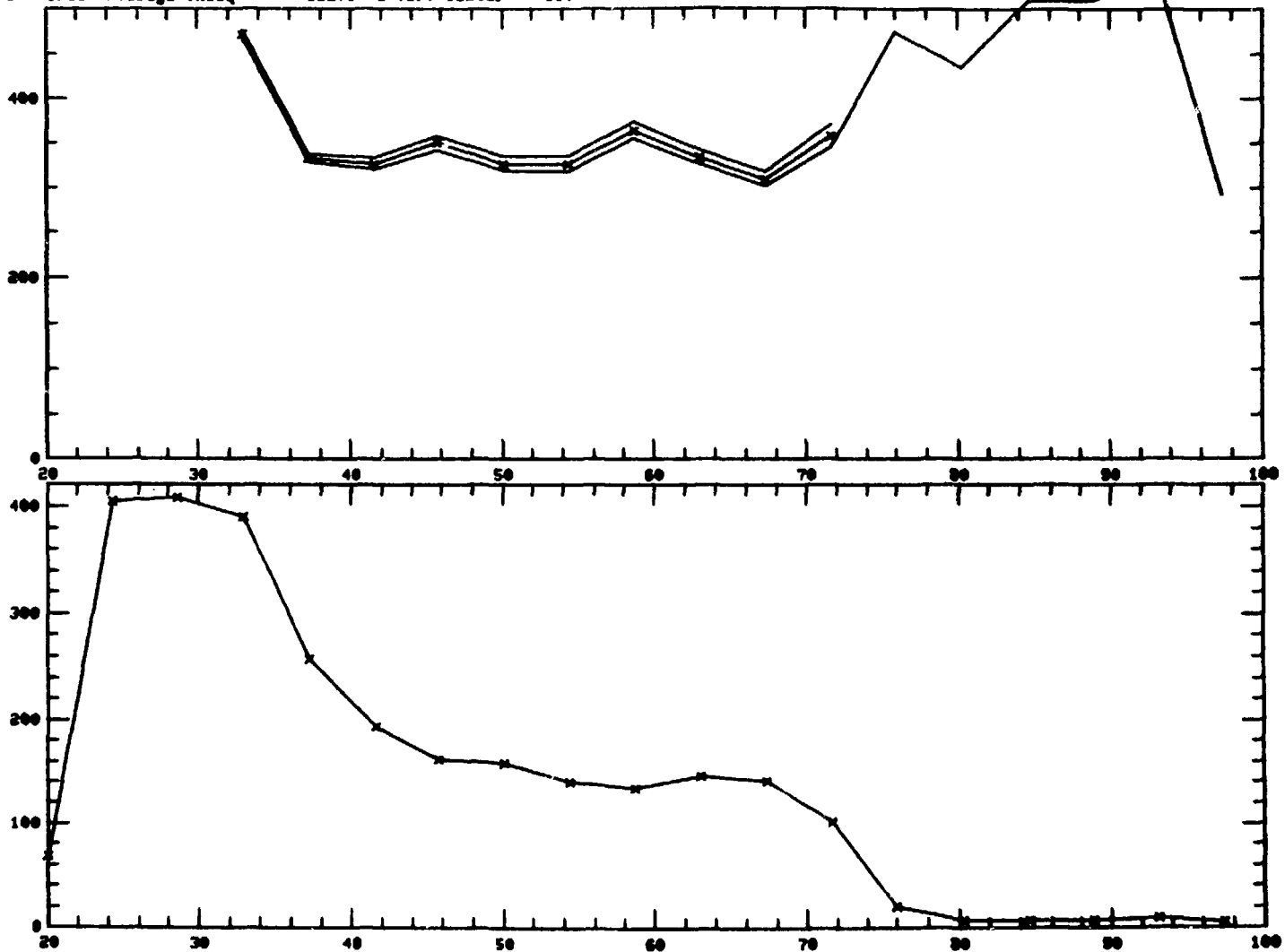


$r_{1/2}$  (cm) vs  $U$  (e.s) and  $z$  (cm)

FR Shot 3007 Type 2 400V 29utorr 10/23/80 11:42 Normalis



Shot 3007 Type 2 400V 20merr 10/23/80 1142  
 Doppler Temperature Guess: 200.0eV -10.0ps  
 19 Times Average Chisq 862.0 3 Var. Center -10.

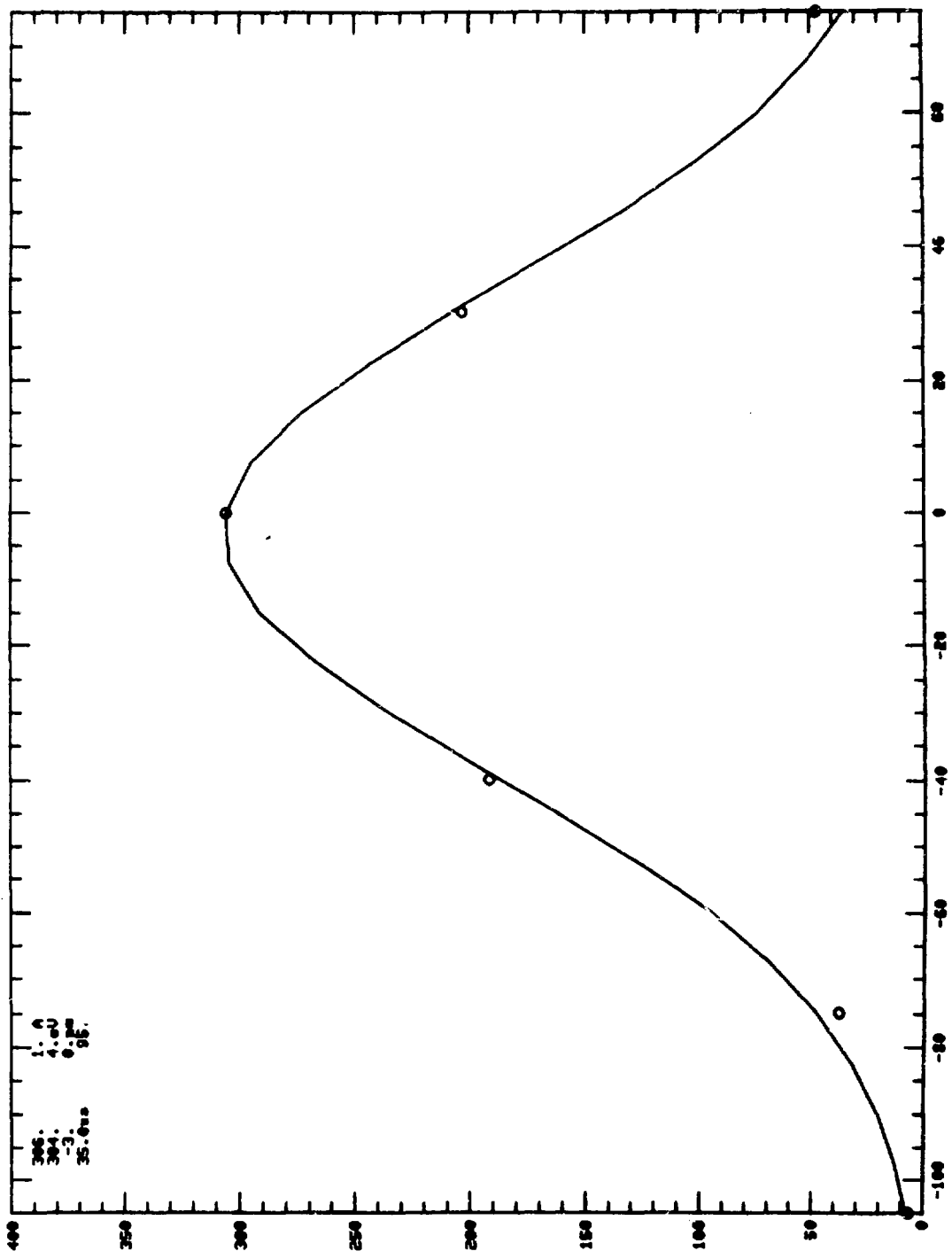


$T_i$  (eV) vs  $t$  (s) and  $I$  (arbitrary units) vs  $t$  (s)



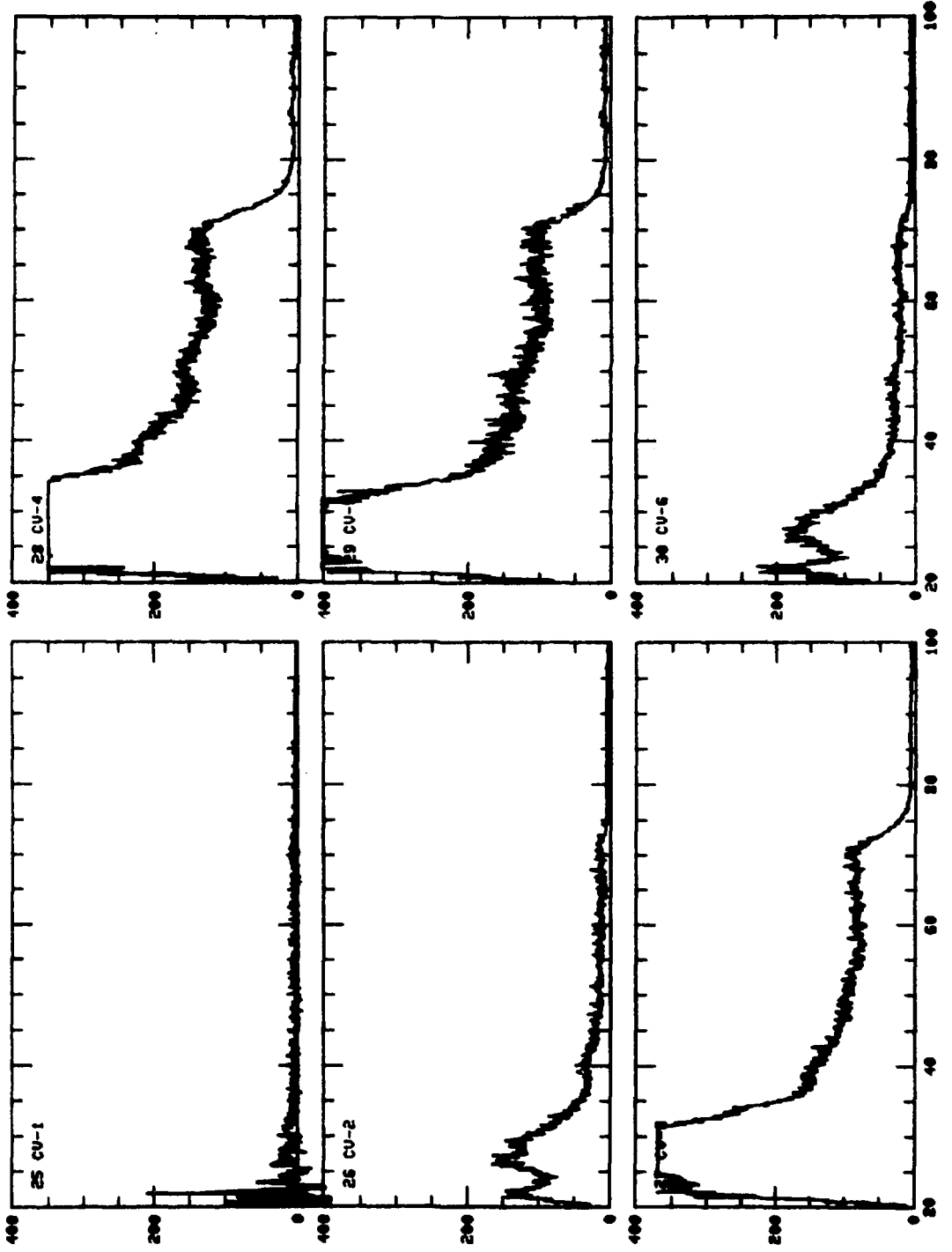
Shot 3007 Type 2 400U 20enterr 10/23/80 1142  
Doppler Temperature Gauss: 200.0uU -10.0um

306.  
304.  
-3.  
35.0us  
1. A  
4. eU  
0. pm  
95.



$I(\Delta\lambda)$  (arbitrary units) vs  $\Delta\lambda$  (pm) at  $t = 10$  ns

FR Shot 3007 Type 2 400U 25nterr 10/23/80 1142 Normalis



I in each CV channel vs t ( $\mu s$ )

Case #4

Shot #2998

$$P_o = 29 \text{ mtorr}$$

$$t_o = 40.0 \text{ } \mu\text{s}$$

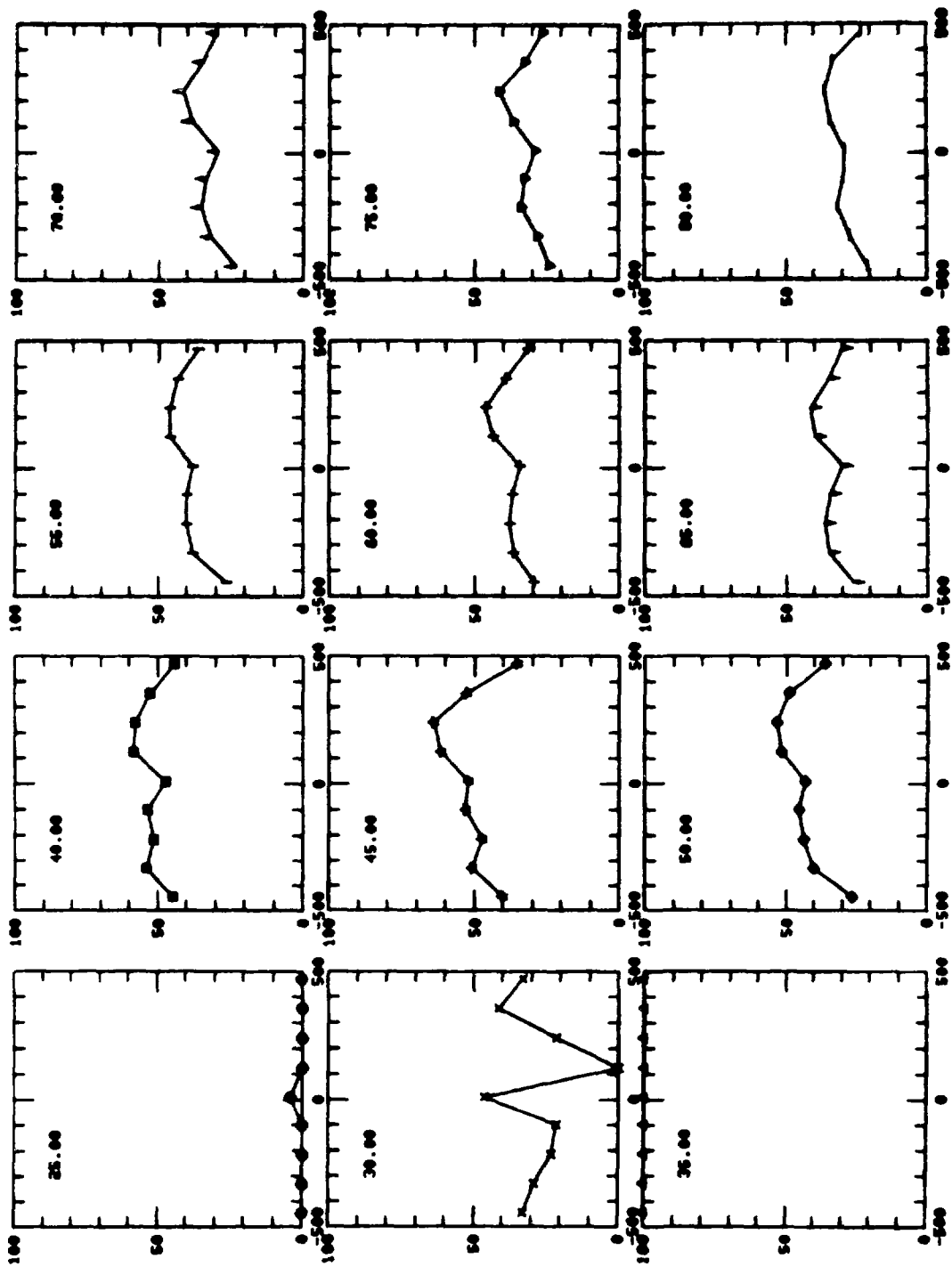
tearing into two FRC's apparent at  $t_o + 10 \text{ } \mu\text{s}$

without any obvious destructive effects

$$\tau_s \approx 35 \text{ } \mu\text{s}$$

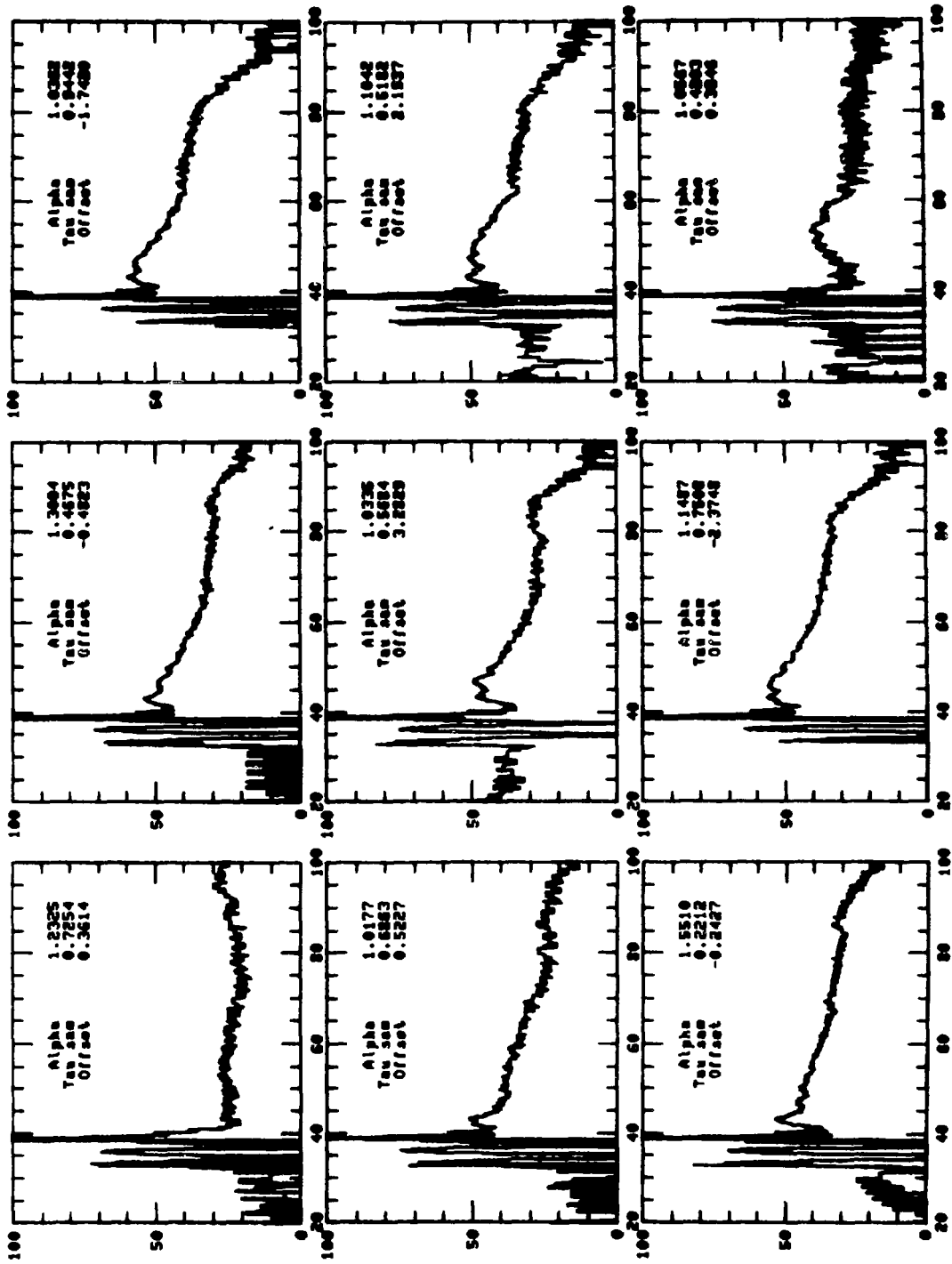
$$\tau_l \approx 50 \text{ } \mu\text{s}$$

FR Shot 2998 Type 2 400U 29Feb88 10/23/00 1103 Radius



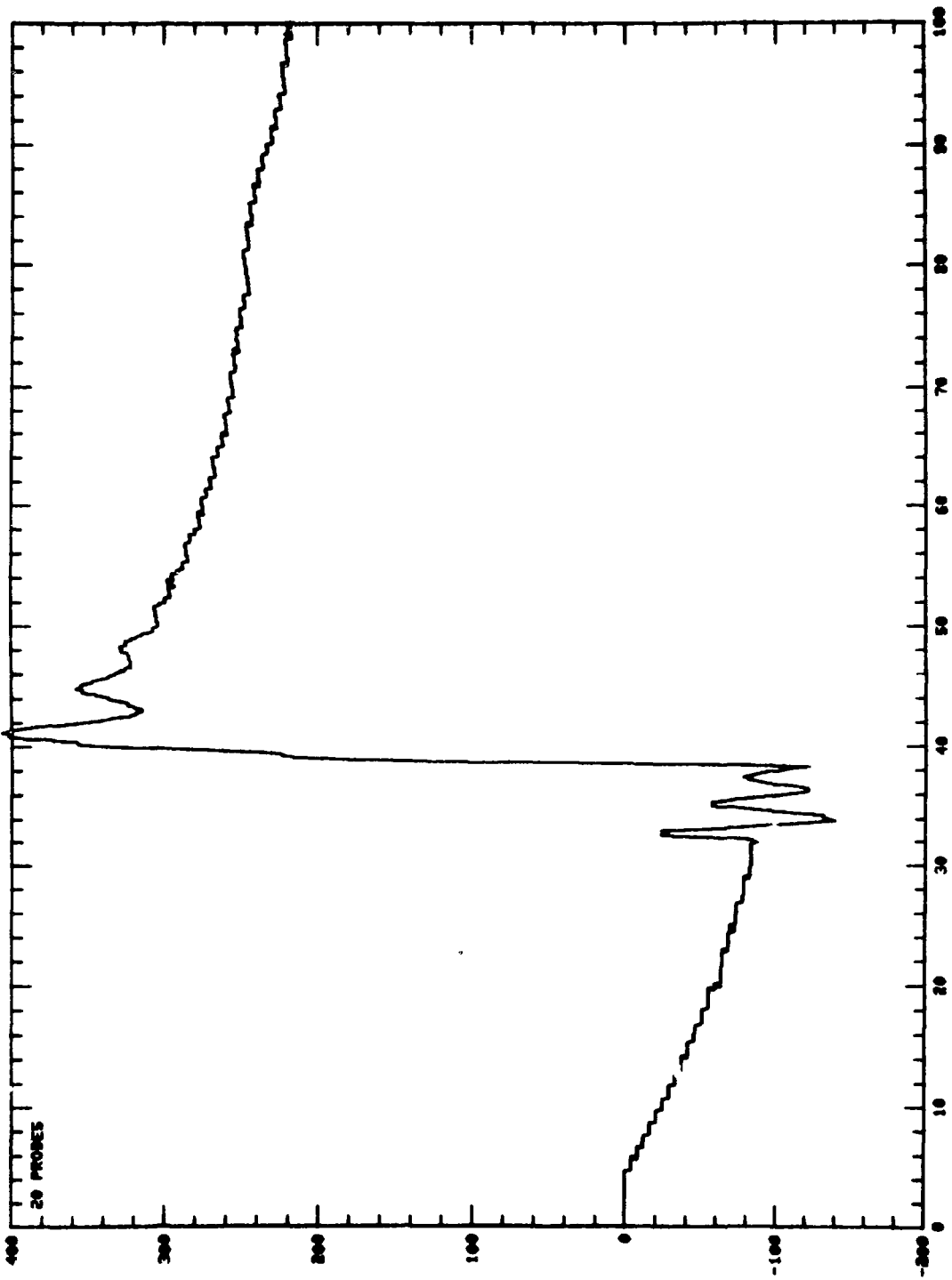
$r_{\Lambda\phi}$  (mm) vs z (mm) and t ( $\mu$ s)

FR Shot 2998 Type 2 400U 29mborr 10/23/86 1103 Radius



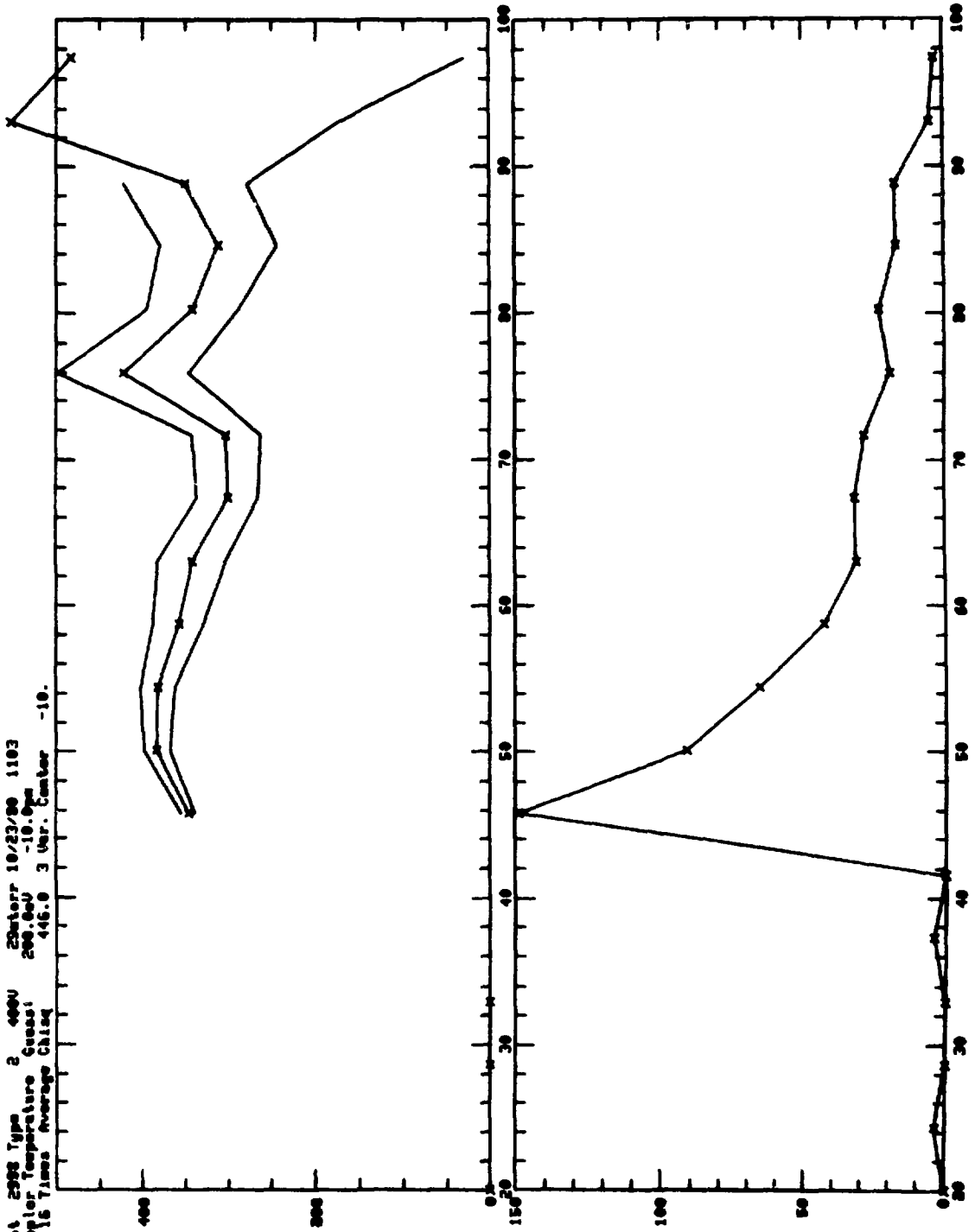
$r$ , (mm) vs.  $\tau$  (s) and  $\alpha$  (rad)

FR Shot 2908 Type 2 400U 25Mberr 10/23/00 1103 Normalis



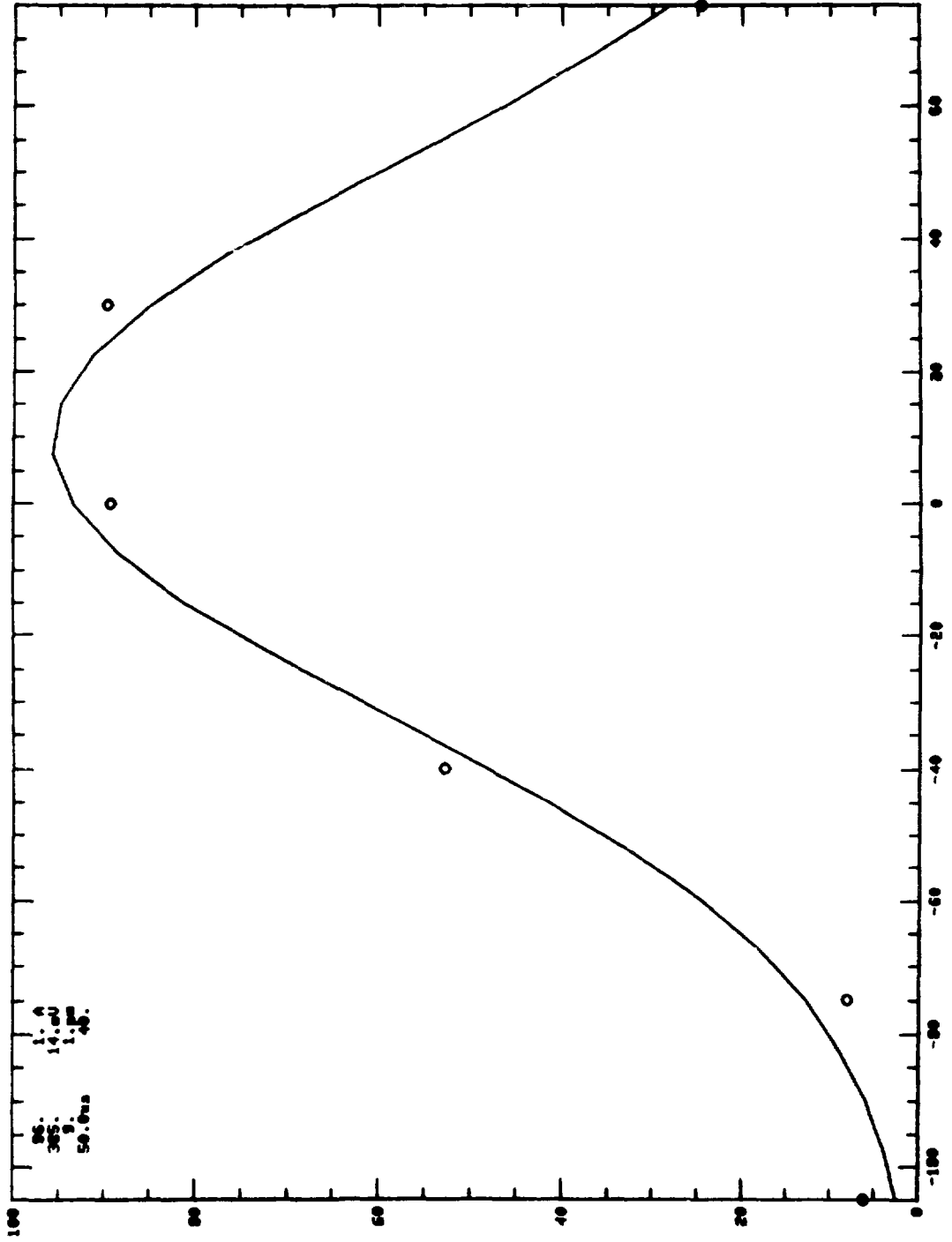
$B_0$  (arbitrary units) vs  $t$  (us) at  $z = 0$

Shot 2988 Type 2 400U 20terr 10/23/80 1103  
 Popler Temperature Guad 200.0u -10.0m  
 15 Times Average Ch14q 446.0 3 Var. Center -10.



T<sub>j</sub> (eV) vs t (s) and I (Arbitrary units) vs t (s)

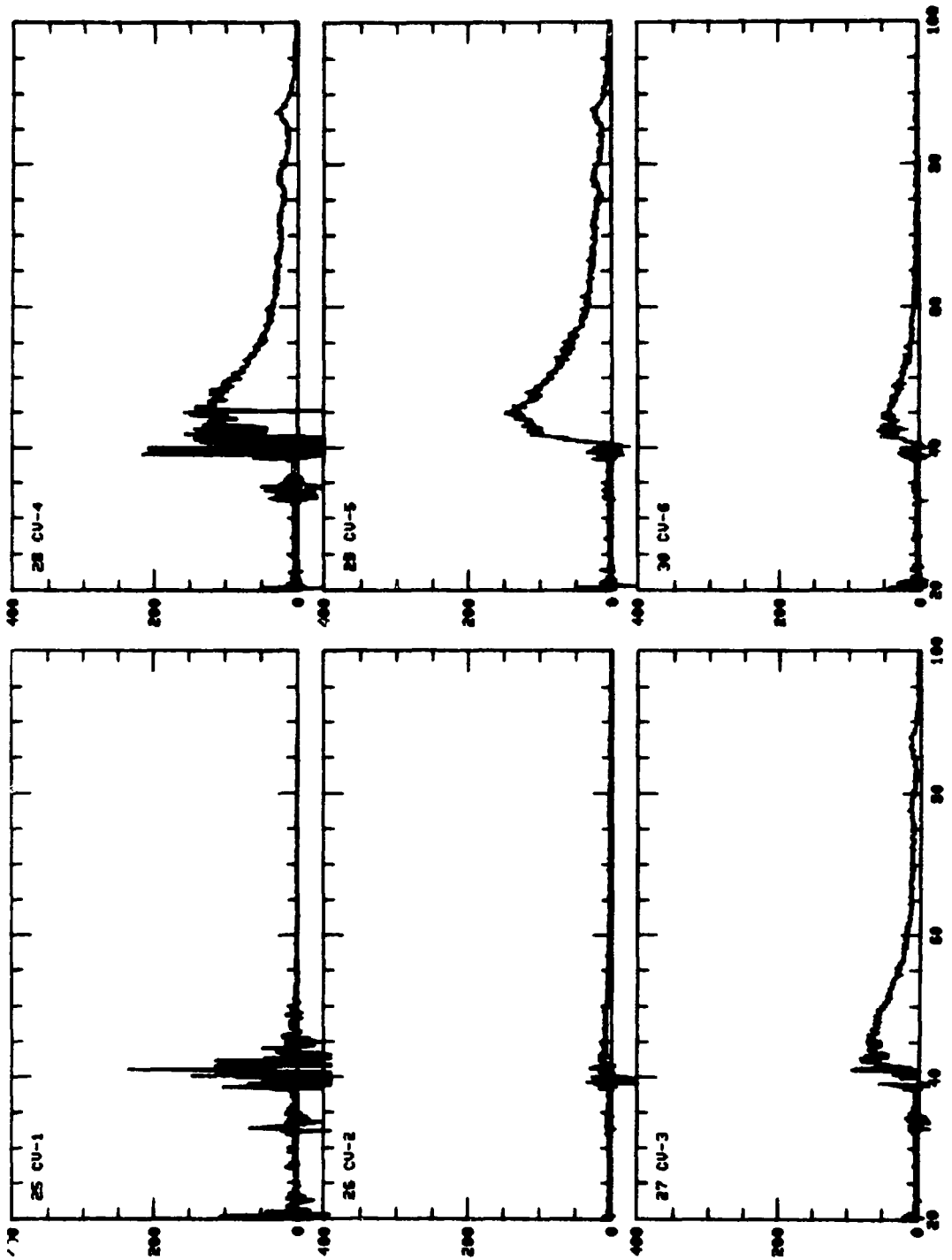
Shot 2998 Type 2 4000 23beterr 10/23/88 1103  
Doppler Temperature Gauss: 266.0mU -10.0pm



$I(\Delta c)$  (arbitrary units) vs  $\Delta c$  (pm) at  $t = 17$  ns



FR Shot 2098 Type 2 400U 20terr 10/23/80 1103 Normalis



I in each CV channel vs t (s)

Case #5

Shot #3145

$P_o = 49$  mtorr

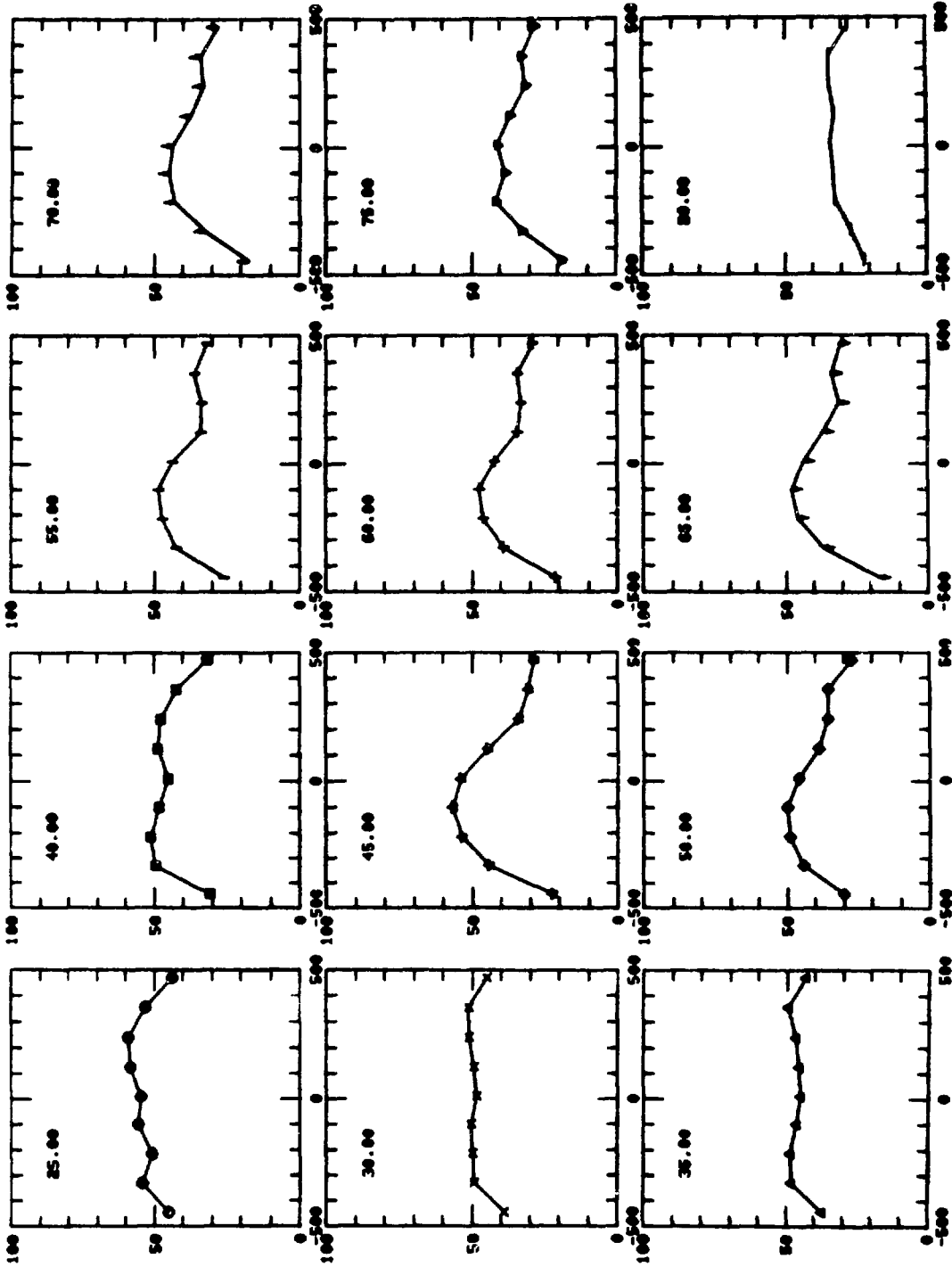
$t_o = 20.0$   $\mu$ s

tearing into two FRC's apparent at  $t_o + 40$   $\mu$ s

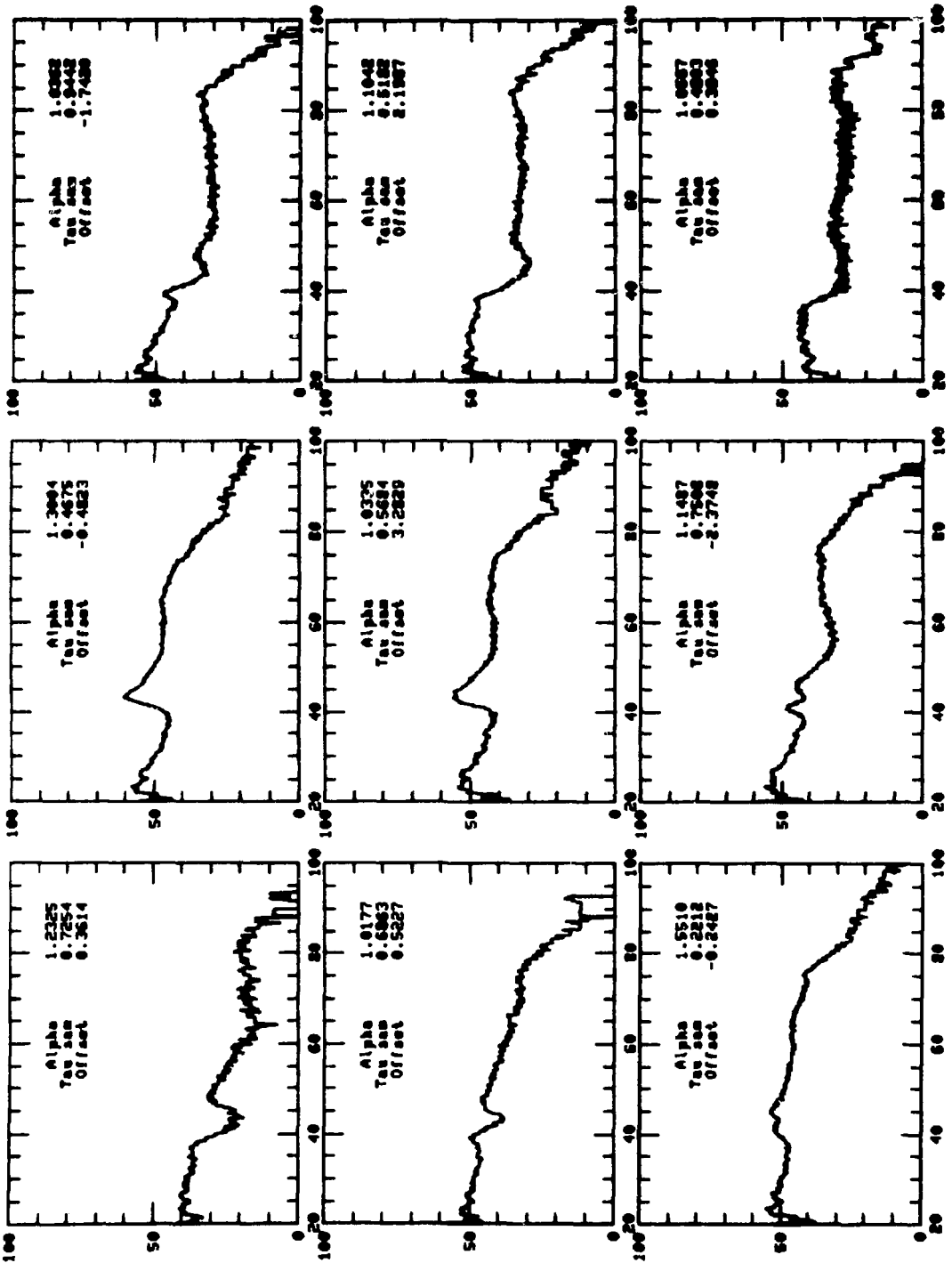
but FRC's coalesce by  $t_o + 45$   $\mu$ s

$\tau_s \approx 50$   $\mu$ s

$\tau_l \approx 65$   $\mu$ s

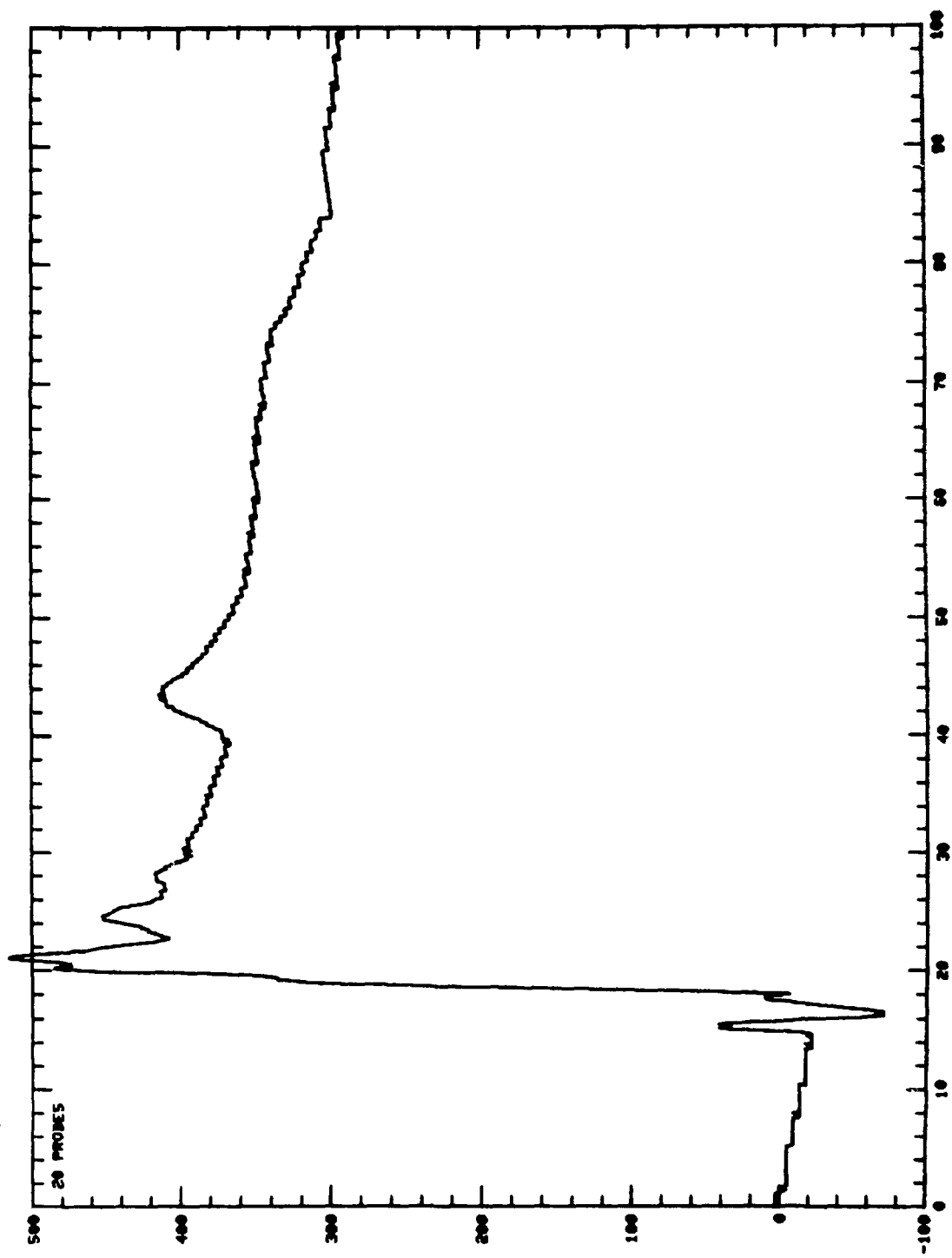


$r_{\Delta\phi}$  (nm) vs  $z$  (mm) and  $t$  ( $\mu s$ )

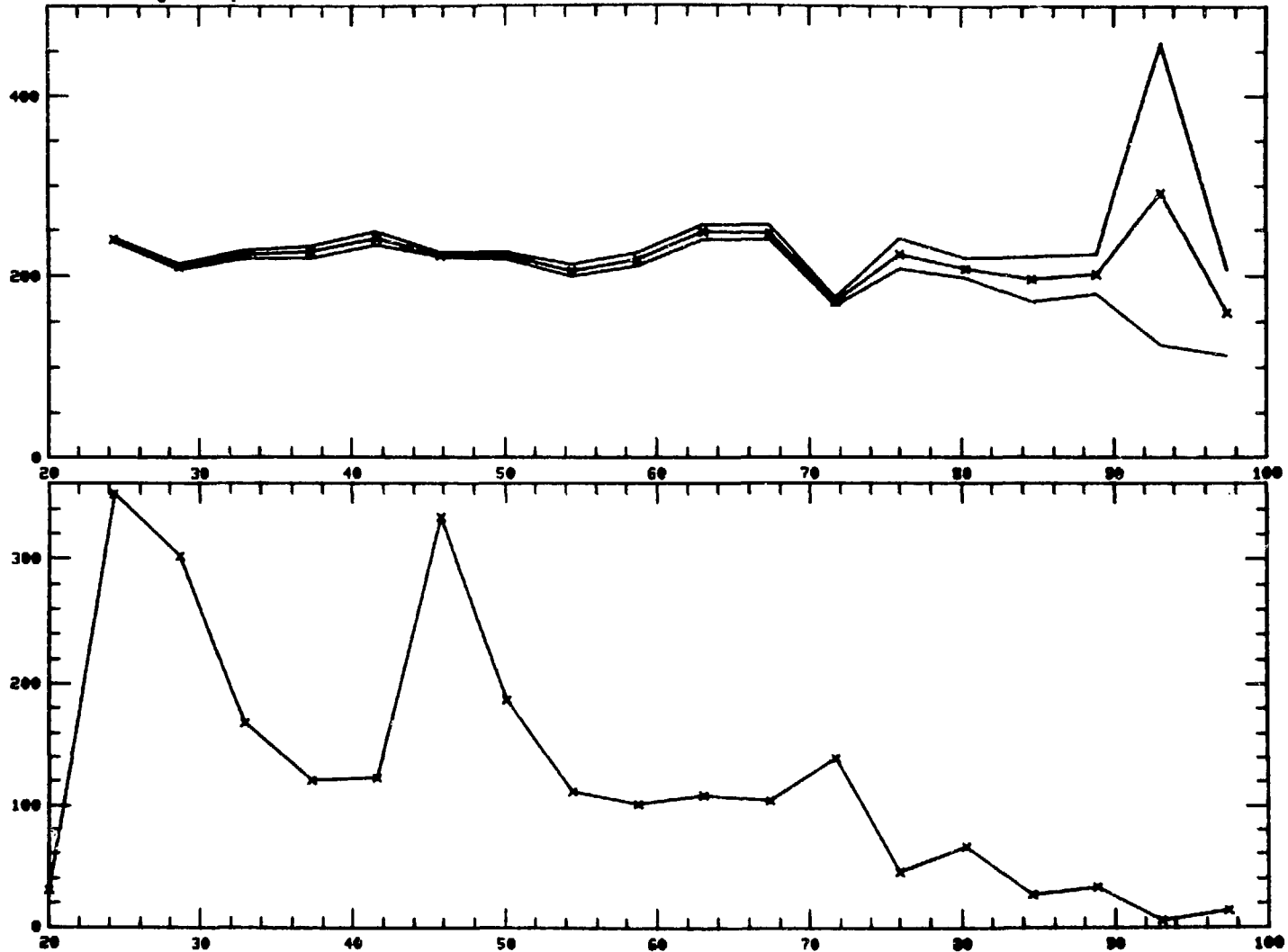


$r_{eff}$  (mm) vs  $t$  ( $\mu s$ ) and  $z$  (cm)

FR Shot 3145 Type 1 400U 49utarr 10/28/00 1336 Normaliz



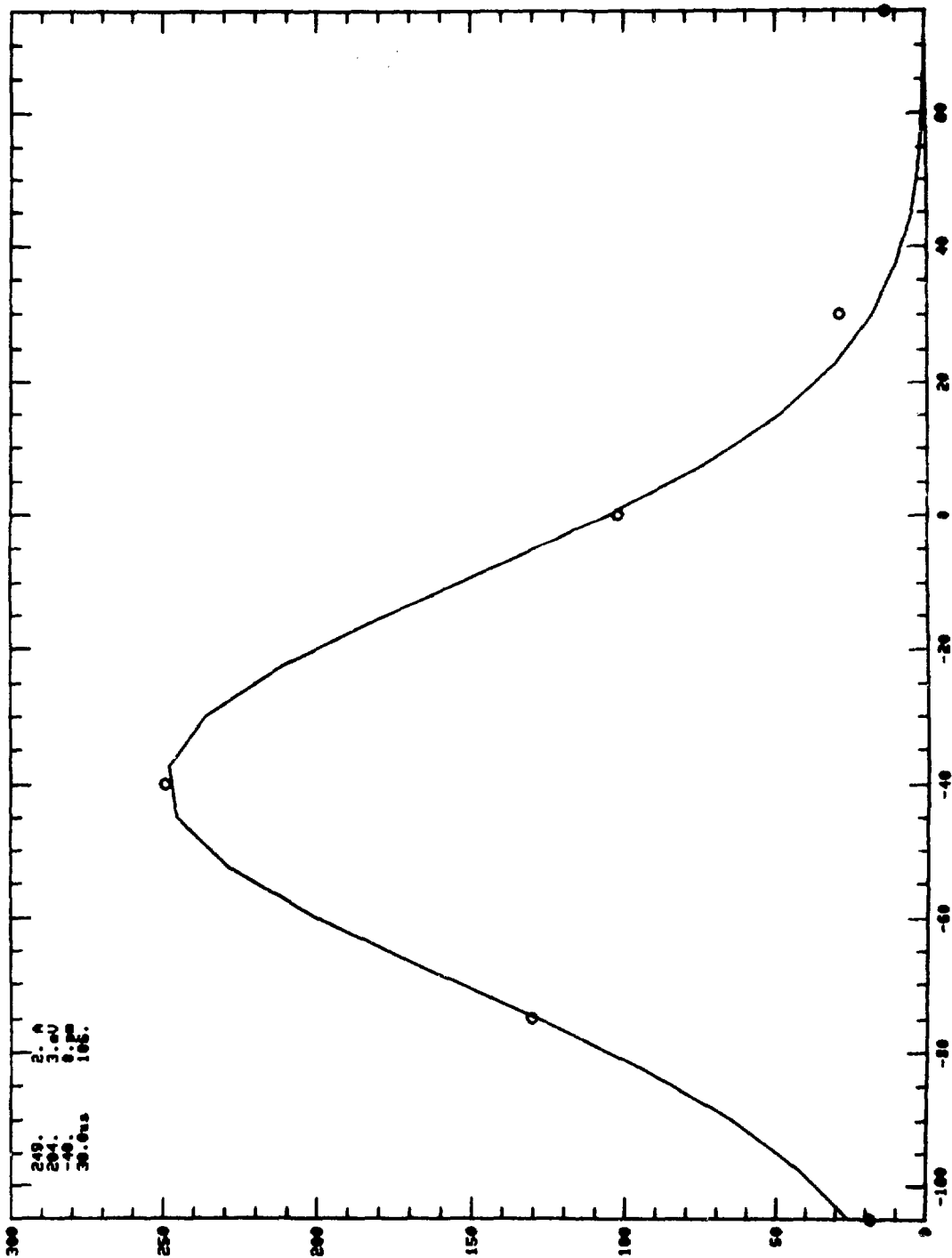
Shot 3145 Type 1 400U 49sterr 10/28/80 1335  
 Doppler Temperature Guess: 200.0eV -10.0ps  
 10 Times Average Chisq 132.4 3 Var. Center -10.



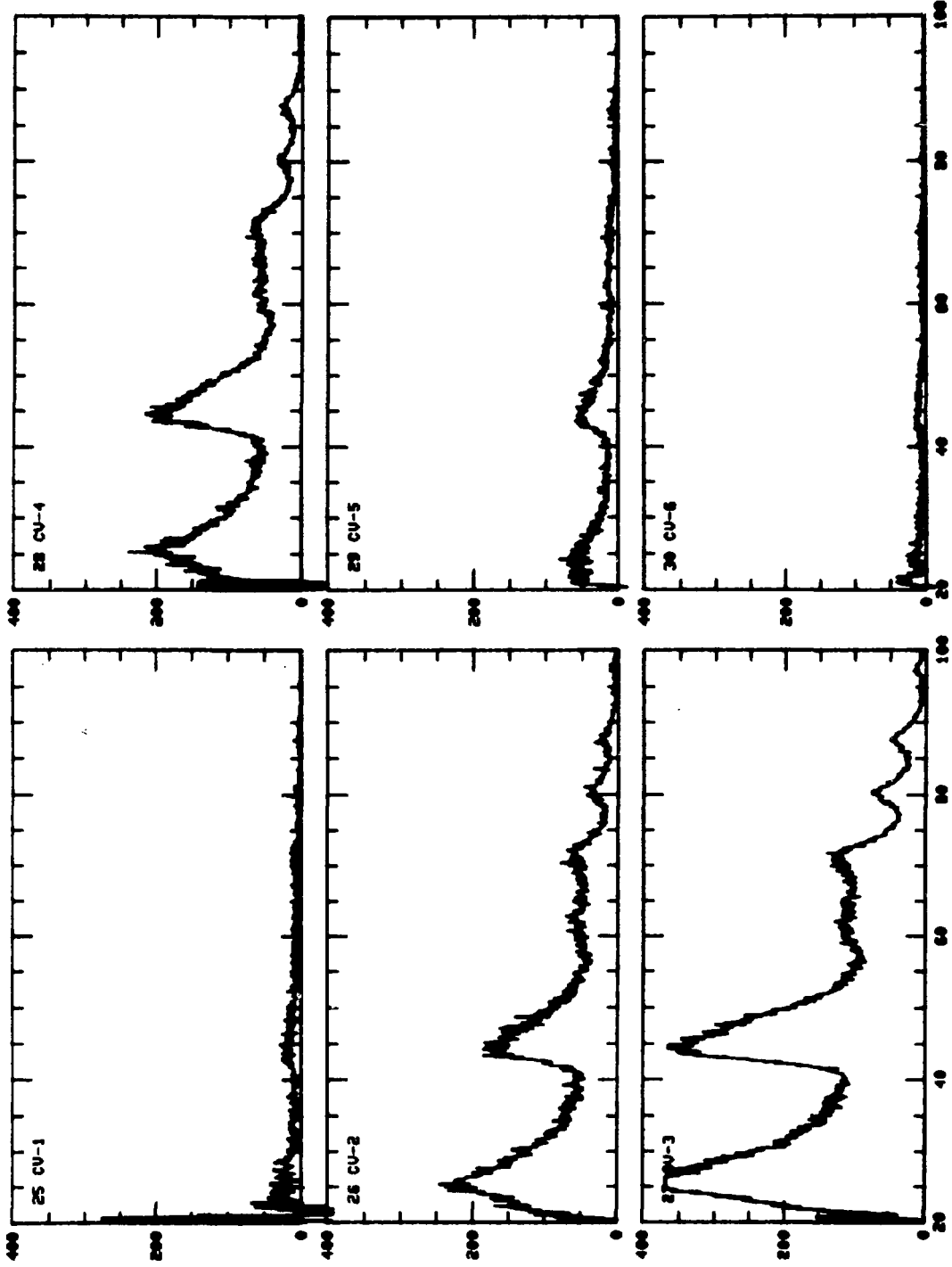
$T_i$  (eV) vs  $t$  ( $\mu\text{s}$ ) and  $I$  (arbitrary units) vs  $t$  ( $\mu\text{s}$ )

Shot 3145 Type 1 400U 42merr 10/28/80 1335  
Doppler Temperature Gauss: 200.0eU -10.0ps

249.  
264.  
-40.  
30.0ms  
2. A  
3. eU  
8. ps  
100.



$I(\text{\AA})$  (arbitrary units) vs  $v$  (pm) at  $t = 17.6s$



I in each CV channel vs t (μs)



Case #6

Shot #3148

$P_o = 49$  mtorr

$t_o = 20.0$   $\mu$ s

tearing into two FRC's apparent at  $t_o + 40$   $\mu$ s,

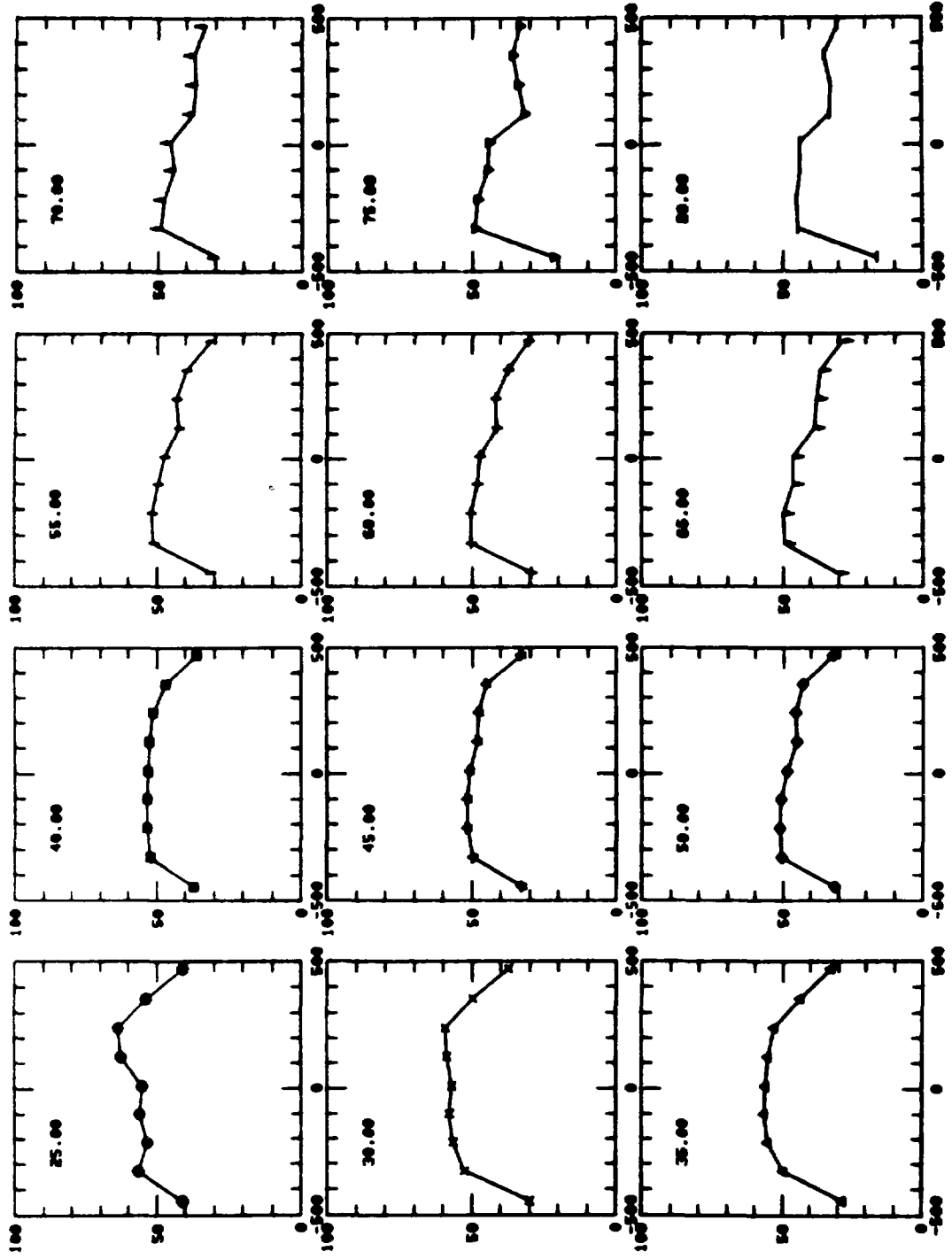
the right FRC translated out of coil at  $t_o + 45$   $\mu$ s,

the left FRC remains intact

$\tau_s \approx 43$   $\mu$ s

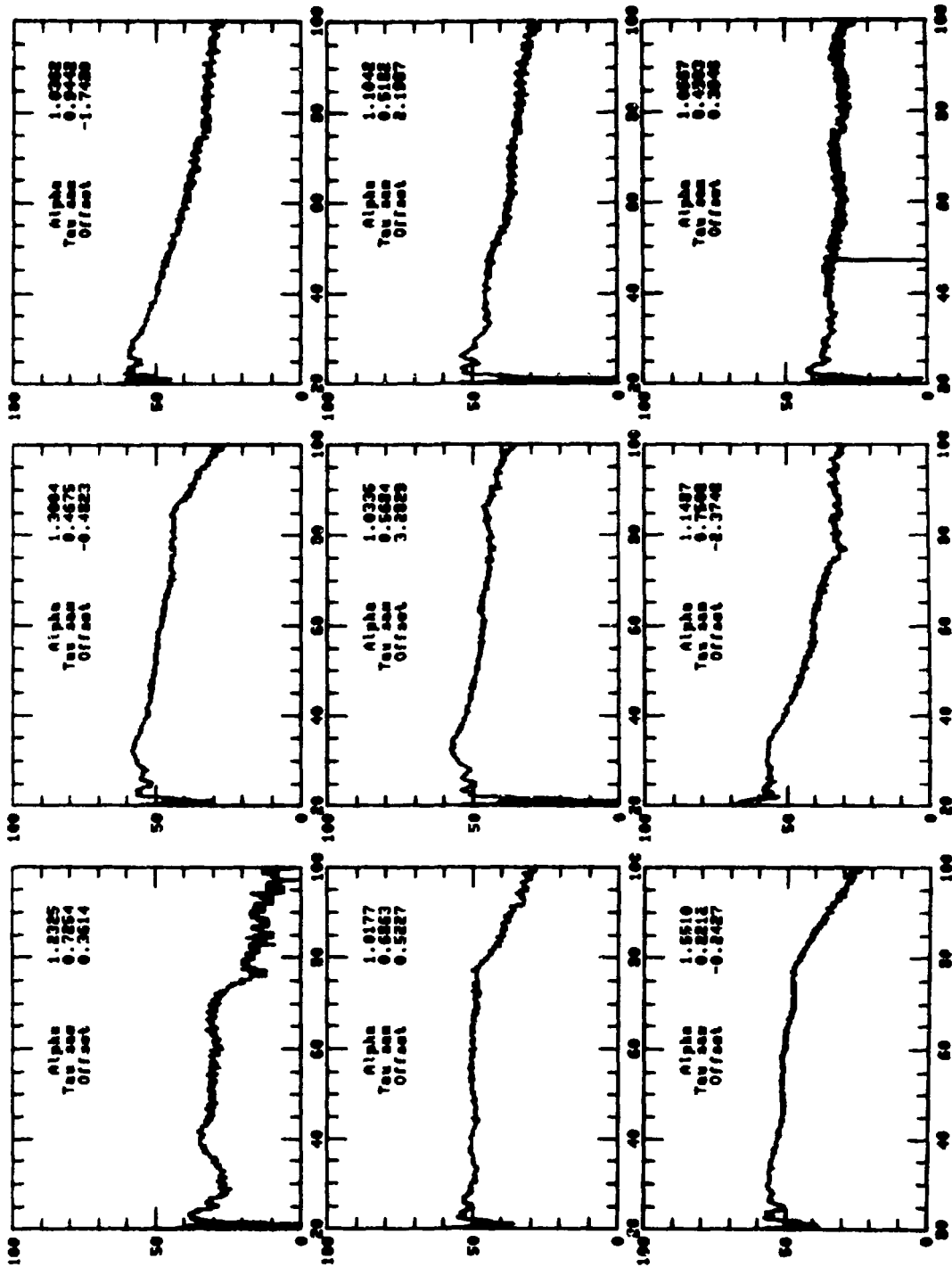
$\tau_l \approx 80$   $\mu$ s

FR Sho's 3148 Type 1 400U 40ntorr 10/28/88 1344 Radius



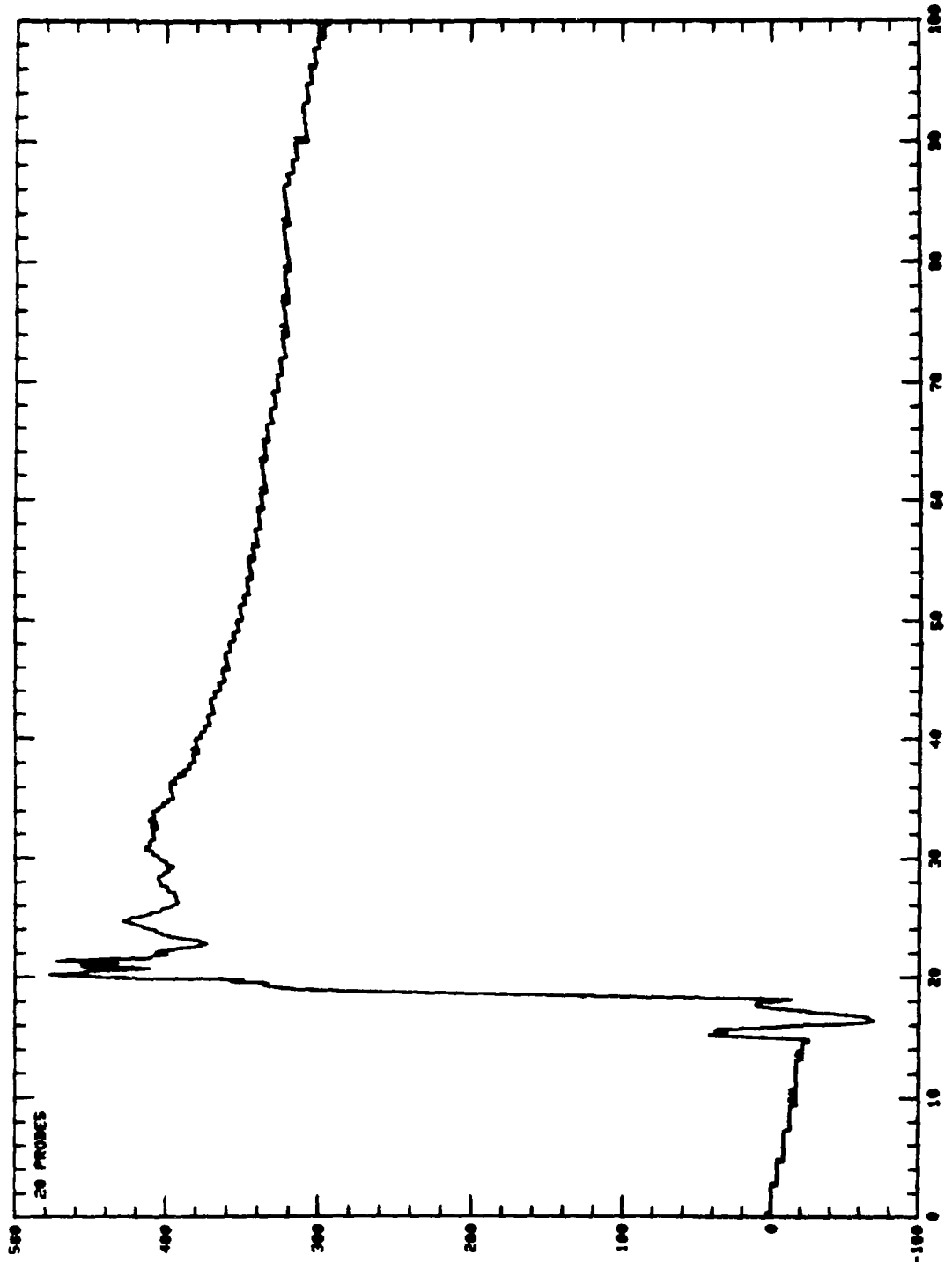
$r_{\Delta\phi}$  (mm) vs  $z$  (mm) and  $t$  ( $\mu s$ )

FR Shot 3148 Type 1 400V 48kerrr 10/22/80 1344 Radius



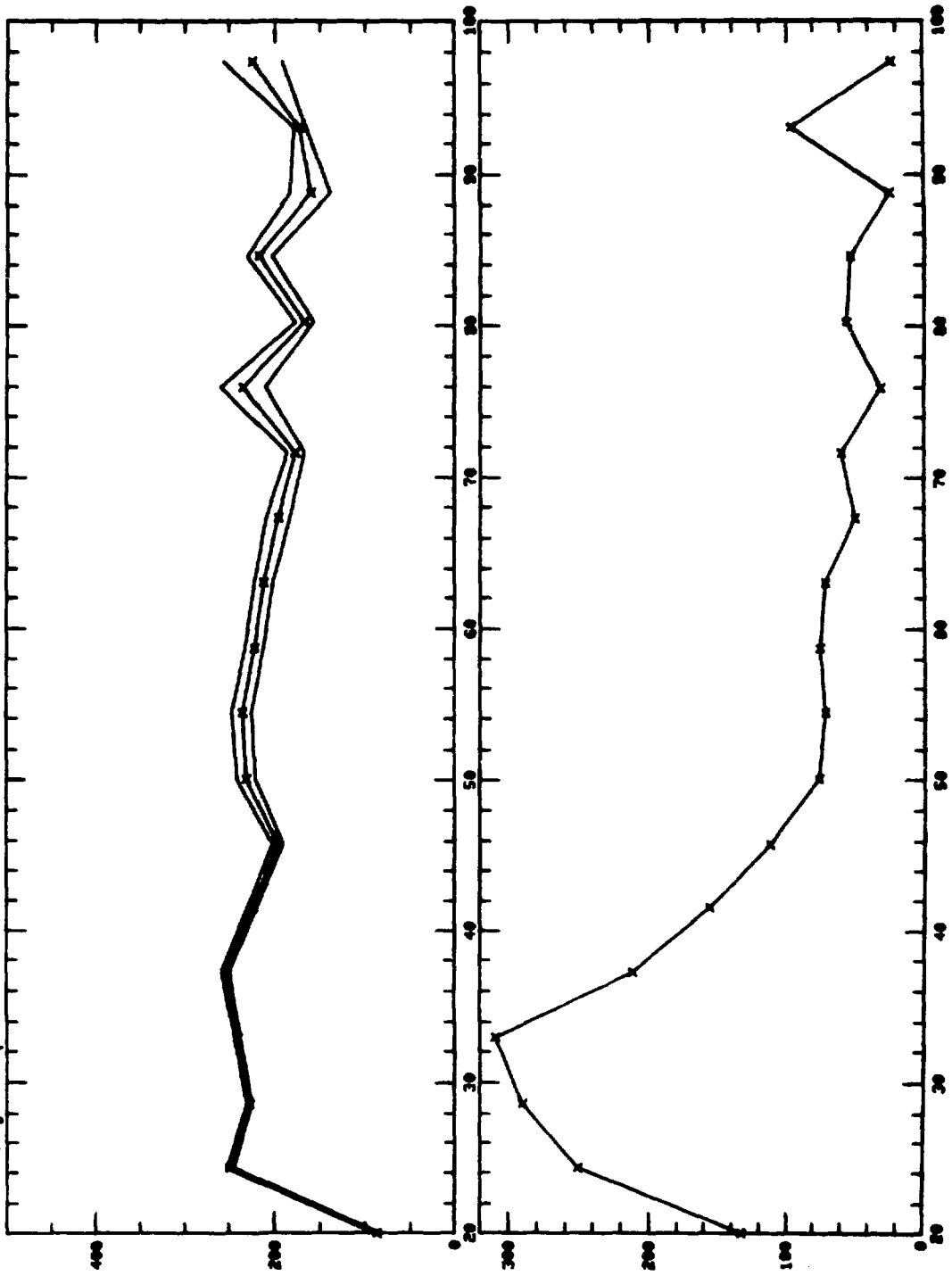
$r_{1/2}$  (mm) vs  $t$  (ms) and  $z$  (mm)

FR Shot 3148 Type 1 4000 49nterr 10/28/00 1344 Normalis



$B_0$  (arbitrary units) vs  $t(\mu s)$  at  $z = 0$

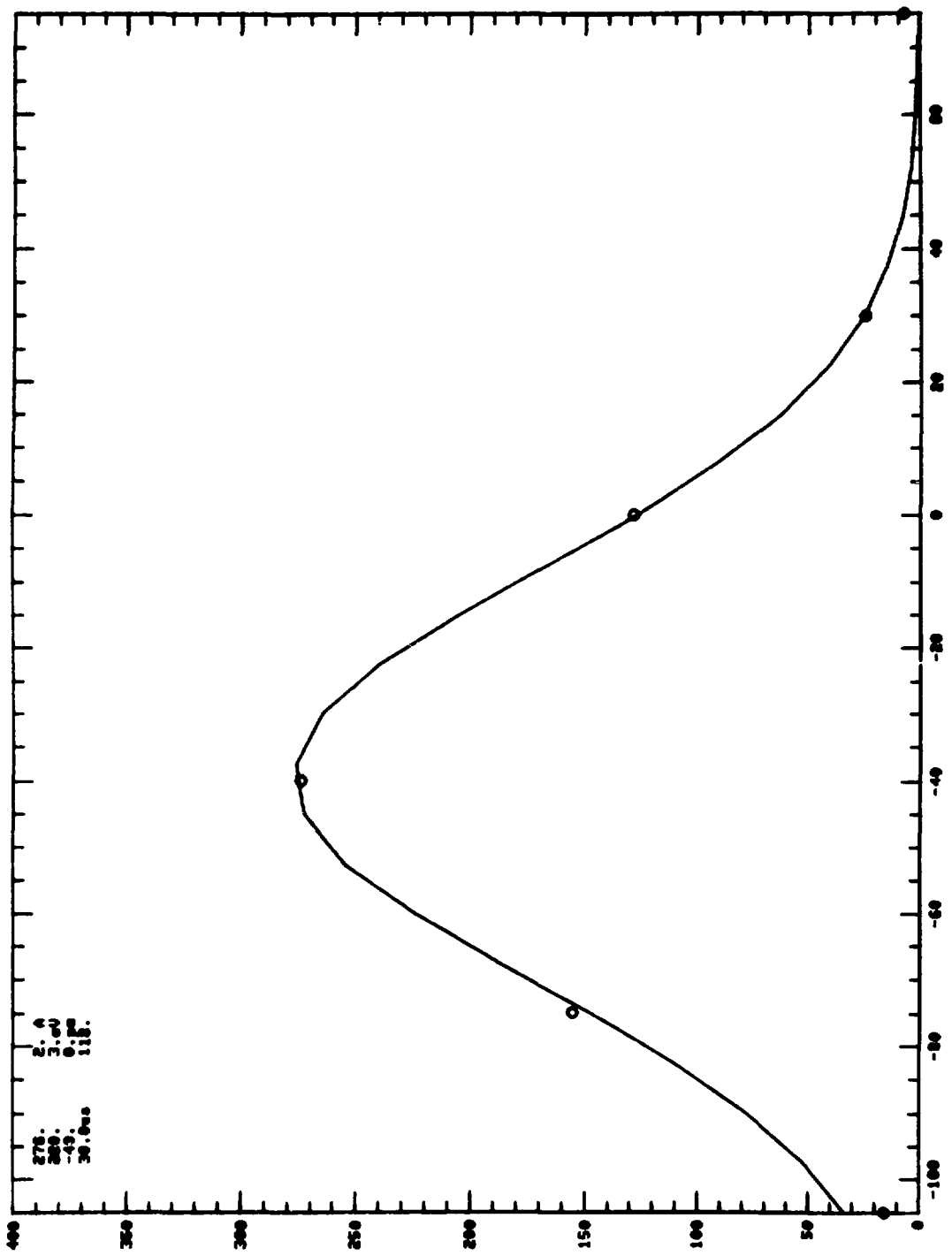
Shot 3148 Type 1 490U 490Uver 10/25/80 1344  
 Doppler Temperature Gauss: 200.0u -10.0g  
 15 Times Average Ch10q 85.0 3 Upr. Center -10.



$T_i$  (eV) vs  $t$  (s) and  $I$  (arbitrary units) vs  $t$  (s)

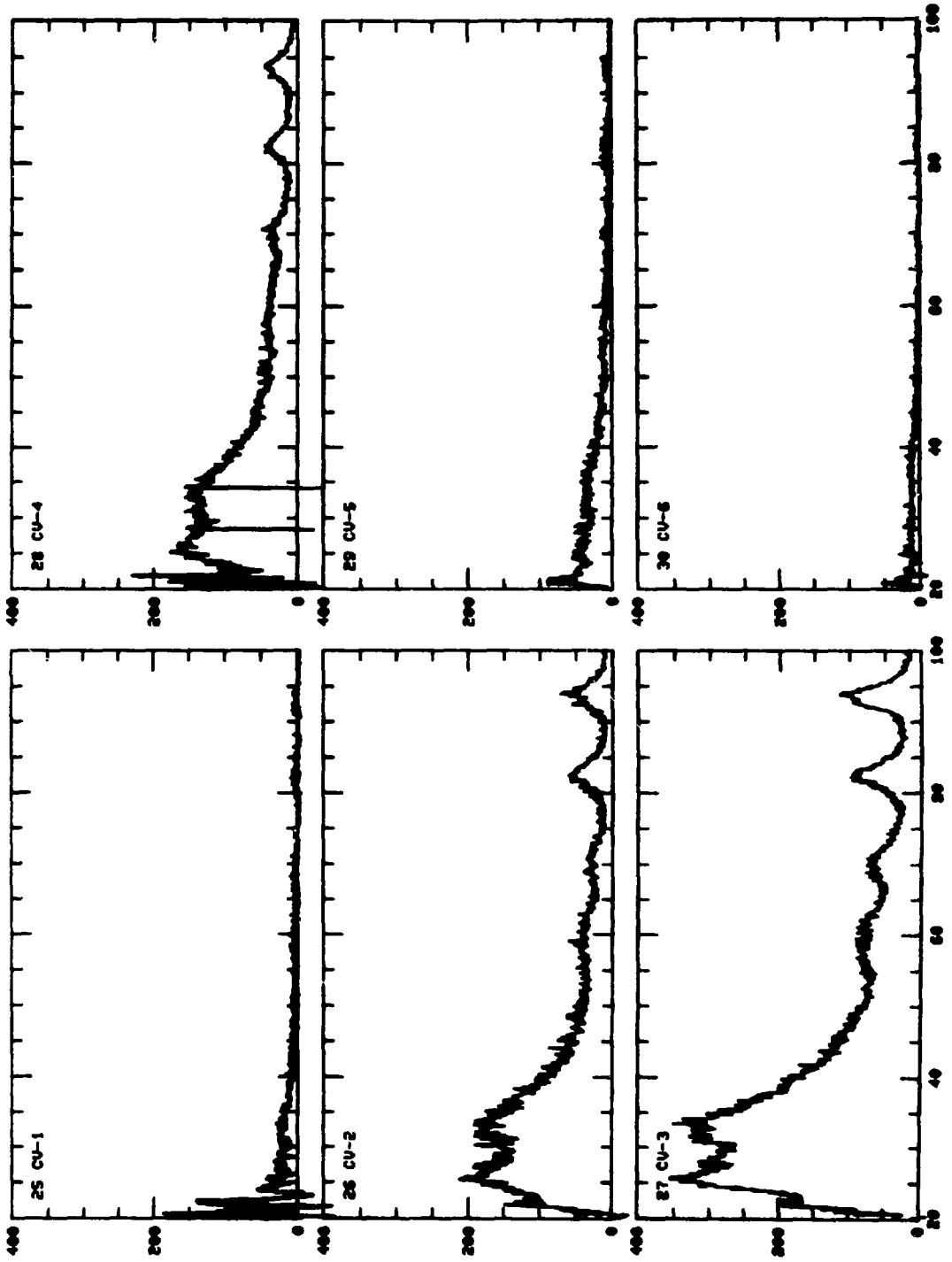
Shot 3148 Type 1 4000 4000 10/25/88 1344  
 Doppler Temperature Guess 200.0uV -10.0ps

276.  
 289.  
 -43.  
 30.8us



I(z) (arbitrary units) vs z (nm) at t = 10 ps

FR Shot 3148 Type 1 400U 49Octarr 10/28/88 1344 Normaliz



I in each CV channel vs  $t$  ( $\mu s$ )

Case #7

Shot #3038

$$P_o = 41 \text{ mtorr}$$

$$t_o = 20.0 \text{ } \mu\text{s}$$

translation of FRC right at  $t_o + 15 \text{ } \mu\text{s}$ ,

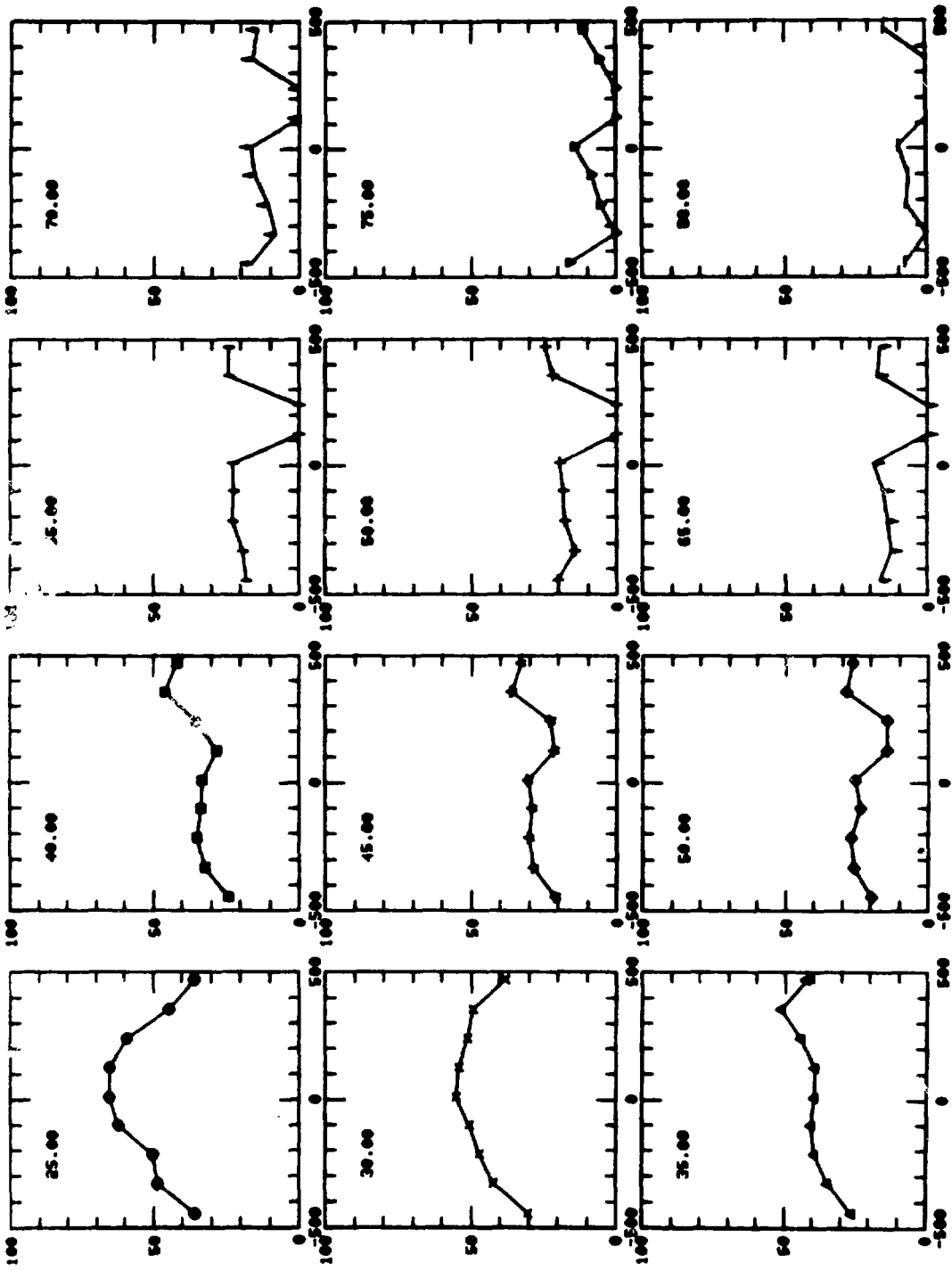
tearing at  $t_o + 20 \text{ } \mu\text{s}$ ,

with rapid destruction of FRC

$$\tau_s \approx 28 \text{ } \mu\text{s}$$

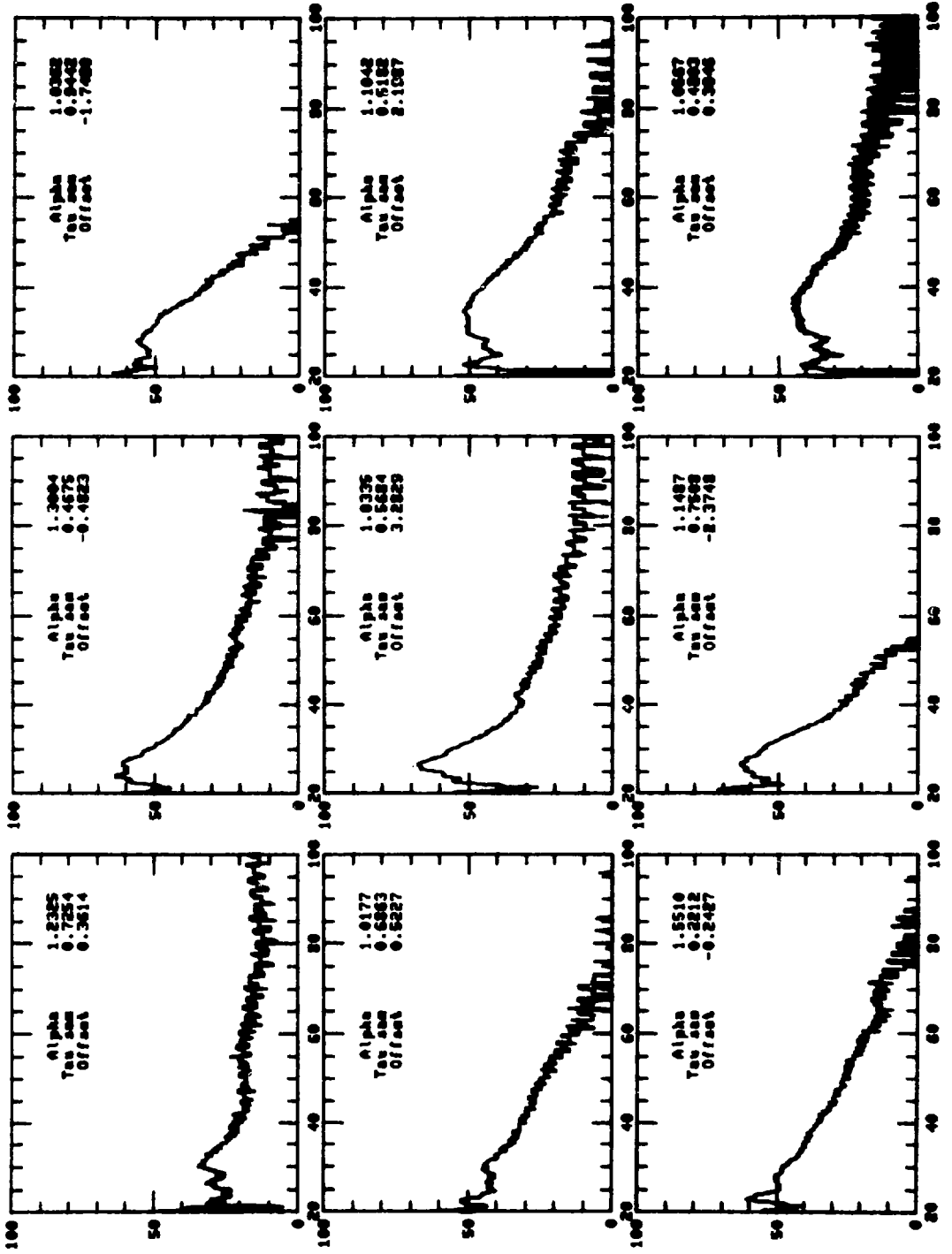
$$\tau_d \approx 30 \text{ } \mu\text{s}$$





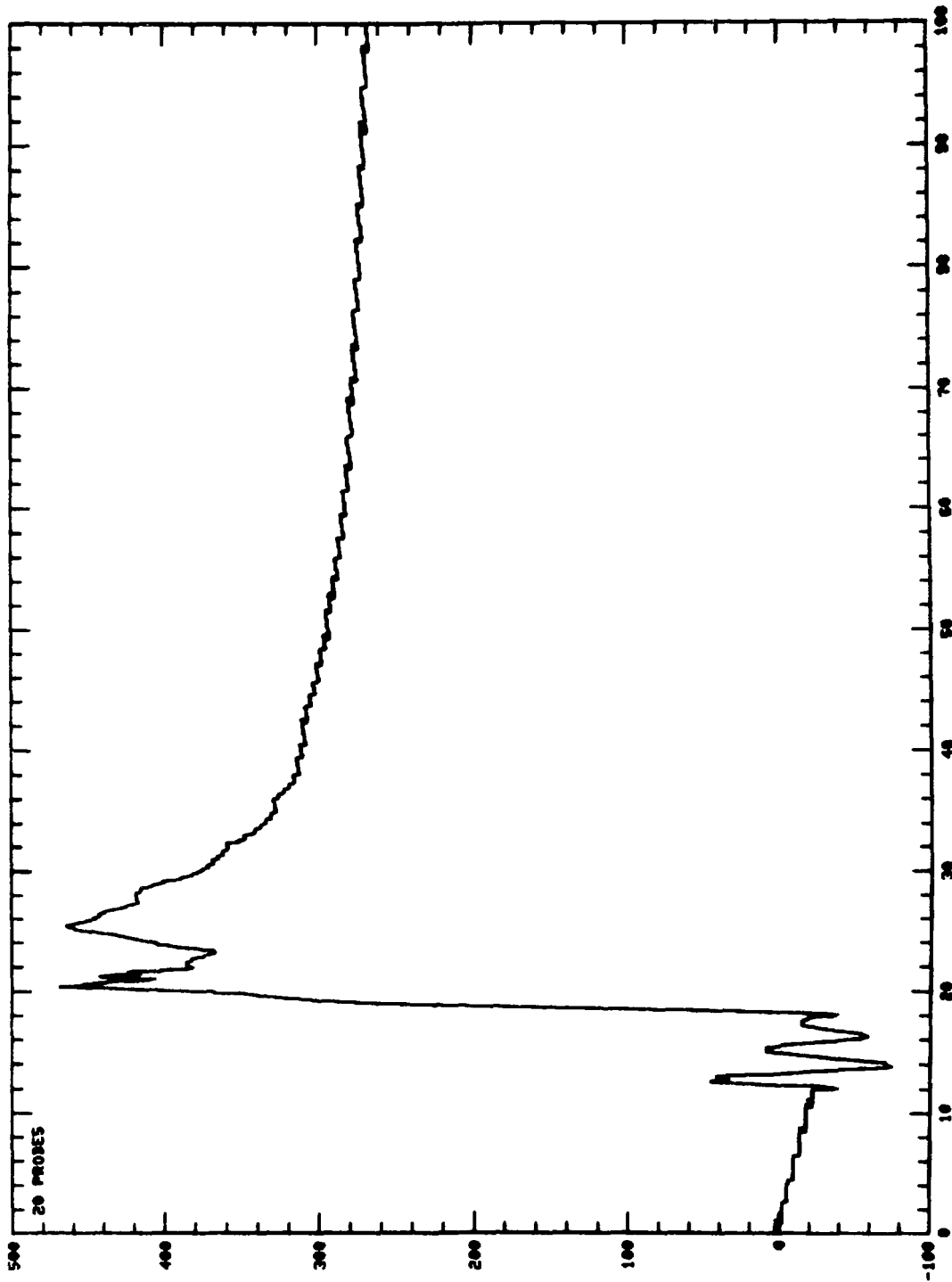
$r_{\Delta\phi}$  (mm) vs  $z$  (mm) and  $t$  ( $\mu s$ )

FR Shot 3038 Type 1 400U 4Imberr 10/24/80 1447 Radius

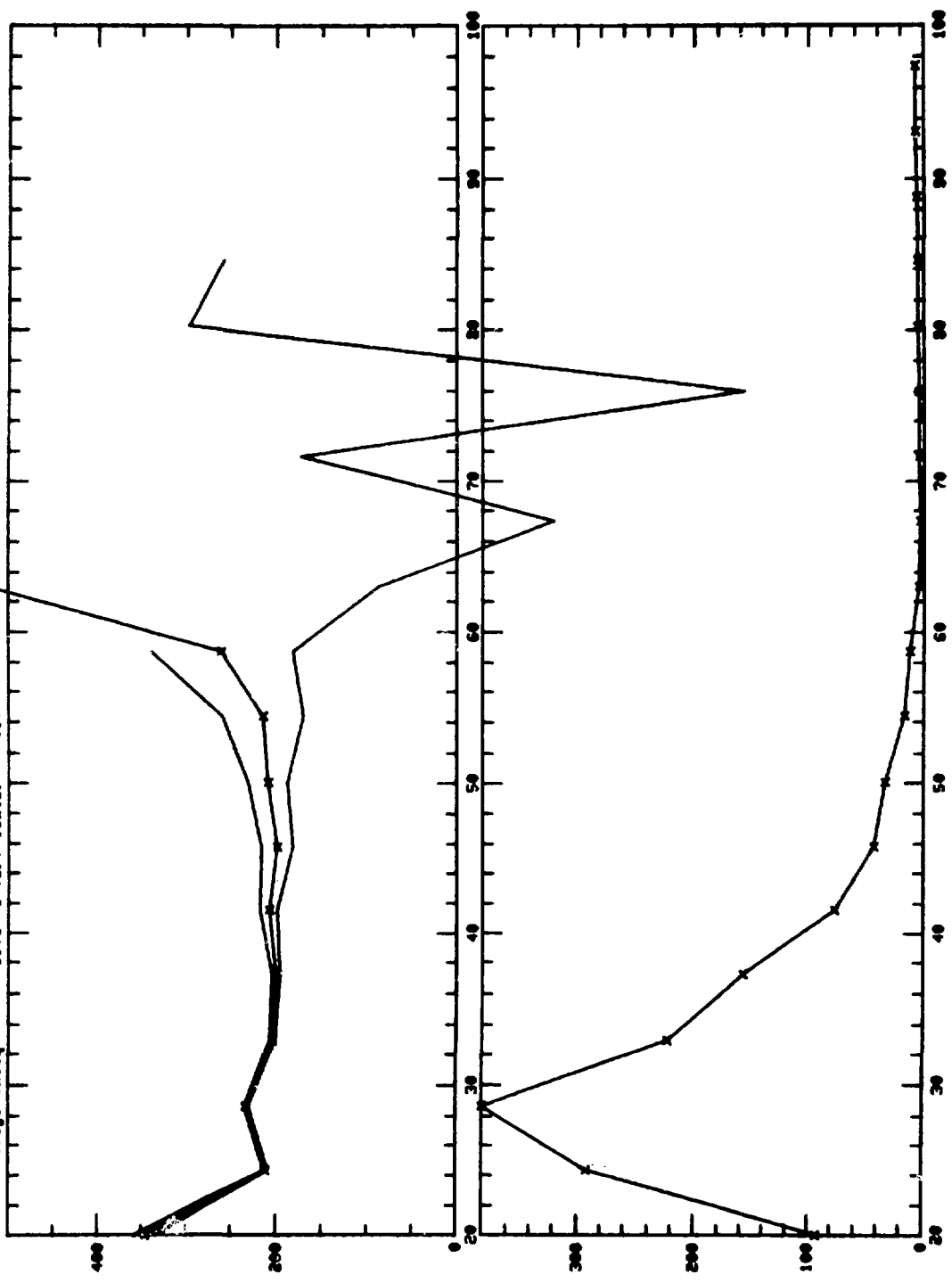


$r_z$  (mm) vs  $t$  (ms) and  $z$  (mm)

FR Shot 3038 Type 1 4000 41mbarr 10/24/88 1447 Normaliz

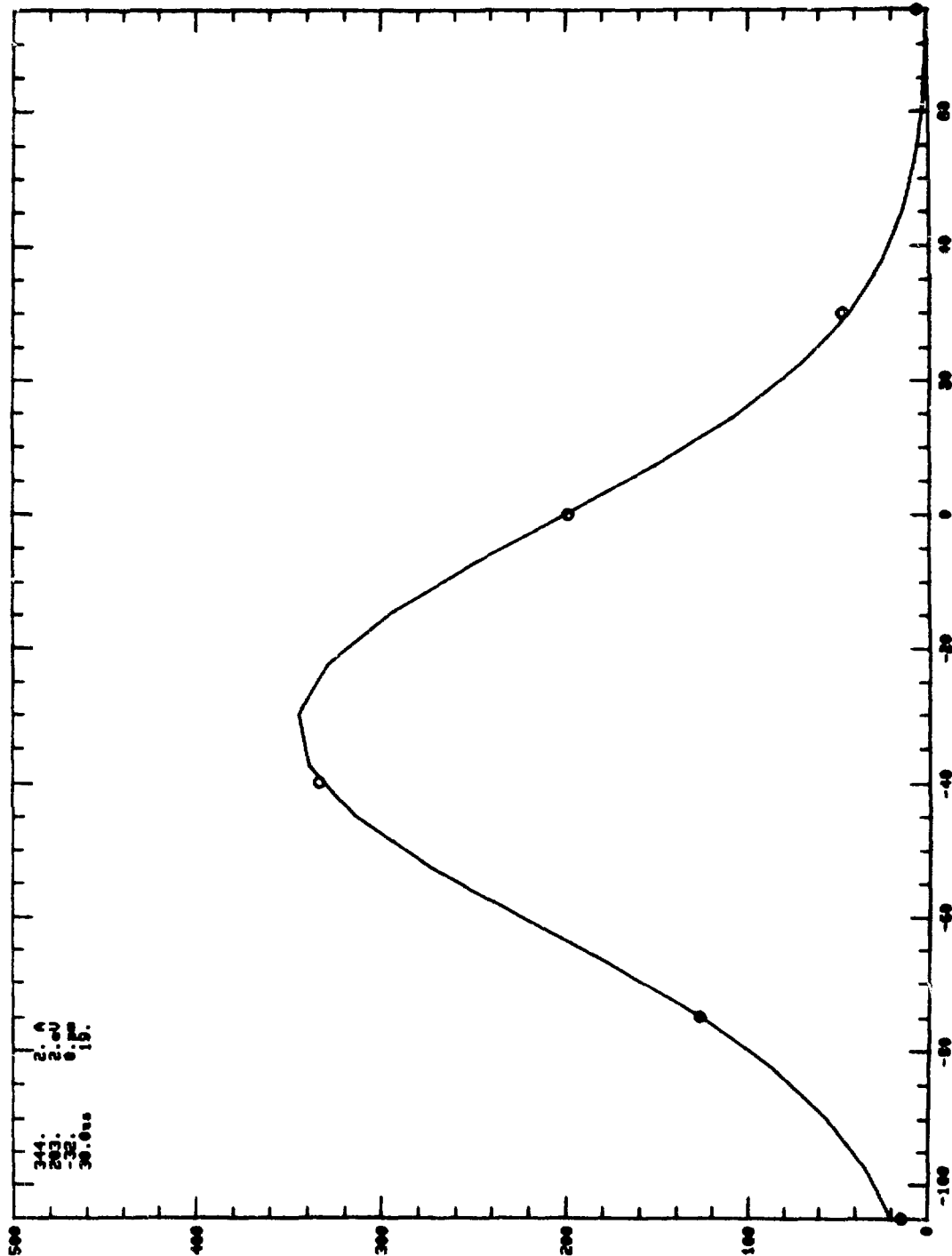


Shot 3028 Type 1 400U 41sterr 10/24/80 1447  
 Doppler Temperature Gauss: 200.0eU -10.0ps  
 19 Times Average Chiq 65.8 3 Var. Center -10.



T<sub>1</sub>(eV) vs t(us) and I(arbitrary units) vs t(us)

Shot 3038 Type 1 4000 41sterr 10/24/89 1447  
Doppler Temperature Guess: 200.0eU -10.0ps

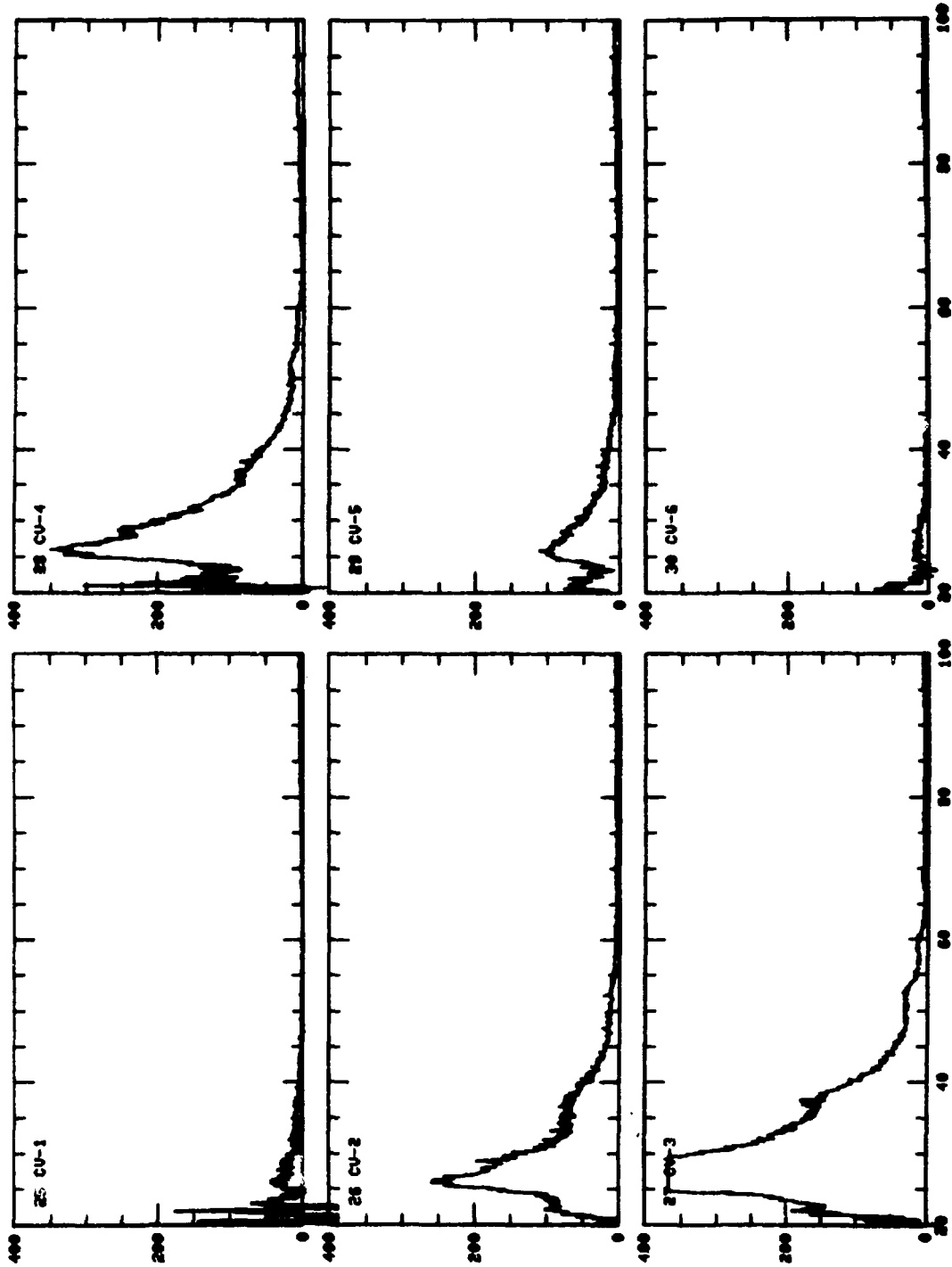


344.  
203.  
-32.  
30.6us

2. A  
2.0U  
0.1ps  
15.

$I(\Delta)$  (arbitrary units) vs  $\Delta$  (pm) at  $t = 10$  ns

FR Shot 3038 Type 1 4000 41aberr 10/24/89 1447 Normalis



I in each CV channel vs t (μs)

## REFERENCES

1. W. T. Armstrong, et al., Phys. Fluids (to be published).
2. J. C. Cochrane, et al., to be published in a LA-MS report.
3. H. P. Furth, J. Killeen, M. N. Rosenbluth, Phys. Fluids 6, 459 (1963).
4. A. Eberhagen and W. Grossmann, Z. Physik 248, 130-149 (1971).
5. J. H. Irby, et al., U. of Md. report #78-241 (1979).