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Measurement of Circulating Beam Size with Flip Target

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About four years ago, an attempt was made to measure the AGS beam size using the flip targets. The results then seemed to give results that were larger than were considered reasonable, and had some unphysical characteristics, like beam shrinkage during acceleration that was faster than the adiabatic damping. Now we have the IPM which also measures the beam size, so we decided to try the flip targets again to see how the two devices compare. Also, the IPM should be able to shed some light on exactly what is happening when the target shaves the beam, so we can understand how to analyze the target results.

There was a feeling four years ago that coupling between the horizontal and vertical planes may be responsible for some of the difficulties. The IPM makes it possible to check this. Such a test was attempted four years ago, by measuring the size in one plane immediately after it had been shaved in the other plane; it was not successful because of the clumsiness of dealing with several targets at once.

The flip target studies have a practical significance. Observed losses on apertures like the H5 kicker or H20 septum are larger than would be expected from the beam size as measured by the IPM. A model which explains the flip target results may also explain these losses, since the mechanism is the same, at least for hard apertures like the kicker.

1. Method

The vertical target at J19 was set up to flip into the beam at nominally 150 msec after T0. The beam loss was measured by taking L20 current transformer readings before and after the loss occurred. The IPM also took a profile and stored it for later analysis. The pentration of the target into the beam, and therefore the amount of beam loss, was controlled by changing the height of the entire drive mechanism. The target was driven into the beam far enough to cause losses of over 80%, which is higher than had generally been done in such tests previously.

It should be noted that the readback of the target height is nonlinear due to a deficiency in the drive controller; the analysis here uses a polynomial fit to a calibration done in 1981.

2. Time structure

The first test looked at the time development of the loss and beam size as the target shaves the beam. The vertical target at J19 was set up so it caused a loss of 44% at approximately 150 msec after T0. The IPM then measured the beam current and size at .5 msec steps from 140 to 160 msec. The results are shown in Figure 1. Note that the IPM measurements are taken on successive beam pulses, so much of the noise in the plots is due to pulse-to-pulse variation in the machine.

When the target shaves the beam, the vertical size decreases, as would be expected. The horizontal size also decreases, but not as much as the vertical. Apparently there is coupling between the H and V planes so that particles with large H amplitude will sometime have a large V amplitude and be scattered out by the target. Comparing the plots of beam size in the two planes shows that the time scale for this coupling to take place is less than a few milliseconds, because the time development of the loss, as measured by the decrease in width, is the same in both planes, within the time resolution of this method. This would be expected, since the coupling occurs at a frequency related to the betatron frequency, which is several orders of magnitude higher than the time scale of this measurement.

The loss in either plane takes about 5-7 msec. This is probably just the time from when the moving target first hits the beam to when it is fully extended.

3. Beam size measurement

The beam size was measured by moving the target further and further into the beam, always measuring the beam loss by L20 current readings before and after the target flip time. Again, the IPM program was also running and reading profiles for later analysis. The measurements were taken from both the top and the bottom of the beam, using the upper and lower arms of the target, because, although the loss data should be symmetrical, it is not known a priori where the center is to sufficient accuracy.

Figure 2 shows the beam loss as a function of target position. For comparison, the profile from the IPM is also shown, both the raw data and a gaussian fit. The abscissa for the IPM plot has been adjusted for the ratio of the beta functions at the two instruments, and the vertical scale normalized so the gaussian is one at its center. The IPM profile was taken at the same time in the beam cycle, 150 msec, as the target loss data, so no adjustment is needed for beam shrinkage with energy.

The numbers for the data points in Figure 2 are given in Table 1. Below are the machine parameters for this data:

		IPM	J05	J19
beta (x)	(meters)	16.5		21.9
beta (y)	(meters)	16.5	23.2	
Xp	(meters)	1.9	2.1	

Beam current:	5-6 Tp
IPM size at 150 msec:	4.0 mm
Ratio of betas, J19/IPM:	1.33
IPM size moved to J19:	4.6 mm

4. Model and curve fitting

To compare and understand the data, a model is needed. The following is a short description of a model which seems to work; the theoretical basis for it remains to be proven. Assume the y (vertical) distribution is a gaussian, which is certainly a good fit to the IPM data. Then the y' distribution is also a gaussian, and the y-y' distribution is a two-dimensional gaussian. In the appropriate normalized coordinate system, the y-y' distribution can be described in terms of radius-angle variables, where the distribution is independent of angle and depends on radius only. The angle can thus be integrated out, which gives a factor of r in the remaining radial distribution.

$$f_1(y) = K_1 e^{-y^2/2\sigma^2} \qquad \text{one-dim. gaussian}$$

$$f(y,y') = K_2 e^{-(y^2+y'^2)/2\sigma^2} \qquad \text{two-dim. gaussian}$$

$$f(r,\theta) = K_2 e^{-r^2/2\sigma^2} \qquad \text{where } r^2 = y^2 + y'^2$$

$$f_r(r) = \int_{\text{all angles}} d\theta \, f(r,\theta) = K_2' \, r \, e^{-r^2/2\sigma^2}$$

The K factors are the normalizations neccessary to make the integral over all coordinates be unity. Any particle will move at a constant radius over all angles, and the action of the target is to remove all particles beyond a certain radius in this normalized y-y' space. Thus the beam loss as a function of target position will be an integral of the form

$$loss = \int_{r_{target}}^{\infty} dr \, f_r(r) = \int_{r_{target}}^{\infty} K_2' \, r e^{-r^2/2\sigma^2} \, dr$$

Figure 3 is a plot of this function superimposed over the measured data. The curve is made two-sided by reflecting it around r=0; the width and the y corresponding to r=0 are chosen to give a reasonable 'eyeball' fit. The fit is not very good; the data points are much steeper and the width does not agree with the IPM.

Because the vertical shaving has an effect on the horizontal distribution, it is clear that the horizontal coordinate x and angle x' must also enter the picture. Again, let the 4-dimensional phase space x-x'-y-y' be appropriately normalized and transformed to three angle and one radial coordinates. If the angle variables are again integrated out of the four-dimensional gaussian, the remaining radial distribution has the form

$$f_r(r) = K_4' \, r^3 e^{-r^2/2\sigma^2}$$

which is like the two-dimensional case but with an r-cubed factor. If the particle motion is such that the target shaving can be described as the loss of all particles with r > r-target, the loss function will be

$$loss = \int_{r_{target}}^{\infty} K_4' \, r^3 e^{-r^2/2\sigma^2} \, dr$$

This is shown in Figure 4, with the width adjusted to match the data. The fit is much better, and the width agrees with that measured by the IPM (4.45 vs. 4.6 mm rms).

The extension to six dimensions is obvious mathematically, although it is unclear what the six dimensions could be physically. Figure 5 shows the six dimensional curve, with the width adjusted to match the data. The fit is even better, especially in the tails, but the width is different from the IPM measurement.

The preceeding has assumed that the distribution in each coordinate is a gaussian, which matches the IPM profiles quite well. But the IPM data is not sensitive far out in the tails, where the four dimensional loss curve does not match the data. If we start with a radial distribution with the tails suppressed compared to a gaussian, the match with the four-dimensional curve can be improved. Figure 6 shows the loss curve for a radial function where the tails are suppressed by adding an r-sixth term in the exponent. (An r-fourth term did not work as well as this). The figure also shows the two and six dimensional curves for this same radial function.

Note that the distribution with this non-gaussian radial distribution can no longer be factorized into independent x, x', y, and y' distributions. Thus the projection onto the y plane, for example, to show what the IPM would measure, must be done the hard way, by actually doing the integrals. This is beyond the ability of the program which is doing this analysis (Symphony, on IBM-PC) so no such curves are shown here, but they would, obviously, be an interesting check.

5. Horizontal beam size

When the beam is shaved vertically, its horizontal size decreases, although not as much as the vertical. It would seem that if there were enough coupling between the two planes to make the four-dimensional model work, then the sizes in both planes should be equal (corrected for beta, of course) and should remain equal after the shaving. Figure 7 shows the beam sizes as a function of target position, both as measured, and with the horizontal size corrected for momentum dispersion with an assumed momentum spread of 0.17% rms. The momentum spread can be calculated from gap volts and bunch width, but those were not measured during this study.

6. Conclusions and further studies

At the machine conditions during this study, there appears to be a coupling between the horizontal and vertical planes which causes the target loss curve to match the theory for a four-dimensional phase space instead of two-dimensional. But the theory used for the curve fitting in this note is vague on the details. We need a clear understanding of how the coupling or mixing between the planes actually occurs.

The study should be repeated with an attempt to eliminate the coupling, to see if the data will then match a two-dimensional theory. The parameters to vary are the skew quads and the horizontal and vertical tune difference.

The interpretation of the horizontal beam size, as in section 5 above, requires knowing the momentum spread. The needed measurements should be made with any further study. In addition, any theory will probably require knowing the tunes.

The flip target data here, when interpreted with a particular model, agrees with the IPM at these conditions of moderate intensity and beam size. The interesting question is whether the target can be used to help understand the IPM at conditions of high intensity and small beam size, where space charge effects are important in the IPM. It is clear that this requires understanding the model used to interpret the target data.

Figure 6 shows that the losses at an aperture are substantially reduced if they follow a two-dimensional instead of a four-dimensional model. According to E. Gill, the operators vary the skew quads to minimize H5 losses during FEB running. A sweep with the target may show if they have, in fact, found conditions which make the behavior two dimensional.

Table 1. Data

Target loss fractions and IPM widths

AGS#	RTJ19	Y (mm)	LOSS	------IPM------ HOR SIGMA	VER SIGMA
958	584	−15.32	0.002	4.988	3.804
959	562	−14.75	0.005	4.977	3.817
960	537	−14.10	0.007	4.843	3.594
962	537	−14.10	0.004	4.710	3.585
963	512	−13.45	0.013	4.700	3.593
966	485	−12.75	0.027	4.664	3.562
967	461	−12.12	0.048	4.626	3.460
968	459	−12.07	0.049	4.705	3.447
970	410	−10.80	0.125	4.566	3.299
971	382	−10.08	0.188	4.626	3.168
972	381	−10.05	0.192	4.540	3.177
974	360	−9.51	0.258	4.482	3.040
975	358	−9.46	0.235	4.543	3.038
976	335	−8.86	0.319	4.395	2.860
978	307	−8.14	0.421	4.247	2.659
979	304	−8.06	0.454	4.236	2.643
980	284	−7.54	0.511	4.230	2.492
986	257	−6.85	0.605	4.171	2.245
987	236	−6.31	0.691	3.997	2.036
988	233	−6.23	0.714	4.169	2.031
989	198	−5.33	0.798	3.919	1.680
990	202	−5.44	0.787		
991	319	−8.45	0.369	4.364	2.759
992	508	−13.35	0.014	4.803	3.576
993	579	−15.19	0.000	4.895	3.605
994	679	−17.80	−0.002	4.753	3.663
995	717	−18.80	−0.004	4.872	3.690
1059	−596	14.48	0.014	4.926	3.790
1060	−573	13.93	0.018	4.750	3.643
1061	−547	13.30	0.039	4.759	3.582
1062	−535	13.01	0.047	4.646	3.468
1063	−523	12.72	0.060	4.722	3.421
1064	−496	12.06	0.093	4.596	3.317
1065	−473	11.50	0.180	4.917	3.316
1066	−450	10.94	0.188	4.483	3.162
1069	−450	10.94	0.189	4.451	3.172
1070	−450	10.94	0.228	4.825	3.213
1073	−450	10.94	0.231	4.675	3.200
1074	−425	10.33	0.246	4.423	3.059
1075	−425	10.33	0.255	4.406	3.018
1077	−425	10.33	0.316	4.780	3.033
1078	−399	9.69	0.339	4.356	2.840
1079	−399	9.69	0.391	4.624	2.871
1081	−391	9.49	0.373	4.313	2.806
1082	−376	9.12	0.431	4.328	2.676
1083	−376	9.12	0.418	4.322	2.725
1085	−347	8.41	0.487	4.149	2.481
1086	−347	8.41	0.502	4.157	2.426
1087	−326	7.89	0.581	4.094	2.276
1089	−325	7.86	0.635	4.232	2.239
1090	−296	7.15	0.694	3.935	2.025
1091	−296	7.15	0.720	4.127	2.027
1092	−275	6.63	0.754	3.814	1.810

---(continued)

Table 1 (cont.)

Target loss fractions and IPM widths

1093	-251	6.03	0.808		
1094	-246	5.90	0.828		
1095	-246	5.90	0.842		
1096	-246	5.90	0.829		
1097	-310	7.49	0.658	4.178	2.161
1098	-366	8.88	0.400	4.219	2.649
1099	-399	9.69	0.305	4.350	2.892
1102	-523	12.72	0.056	4.668	3.498
1103	-547	13.30	0.043	4.953	3.689
1104	-574	13.95	0.026	5.000	3.749
1106	-573	13.93	0.012	4.747	3.574

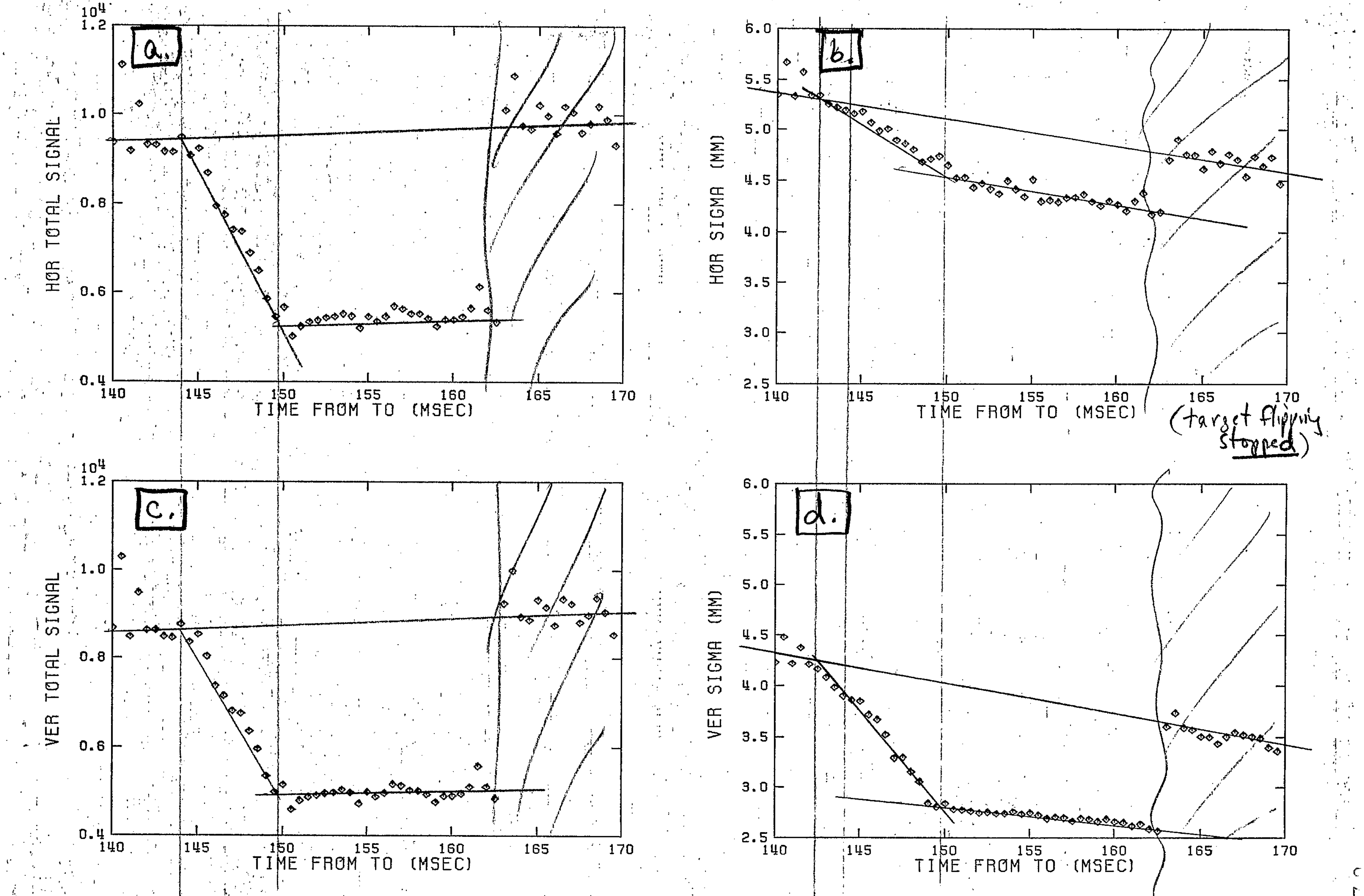

Fig. 1 Time development of 44% beam loss due to vertical target J19.

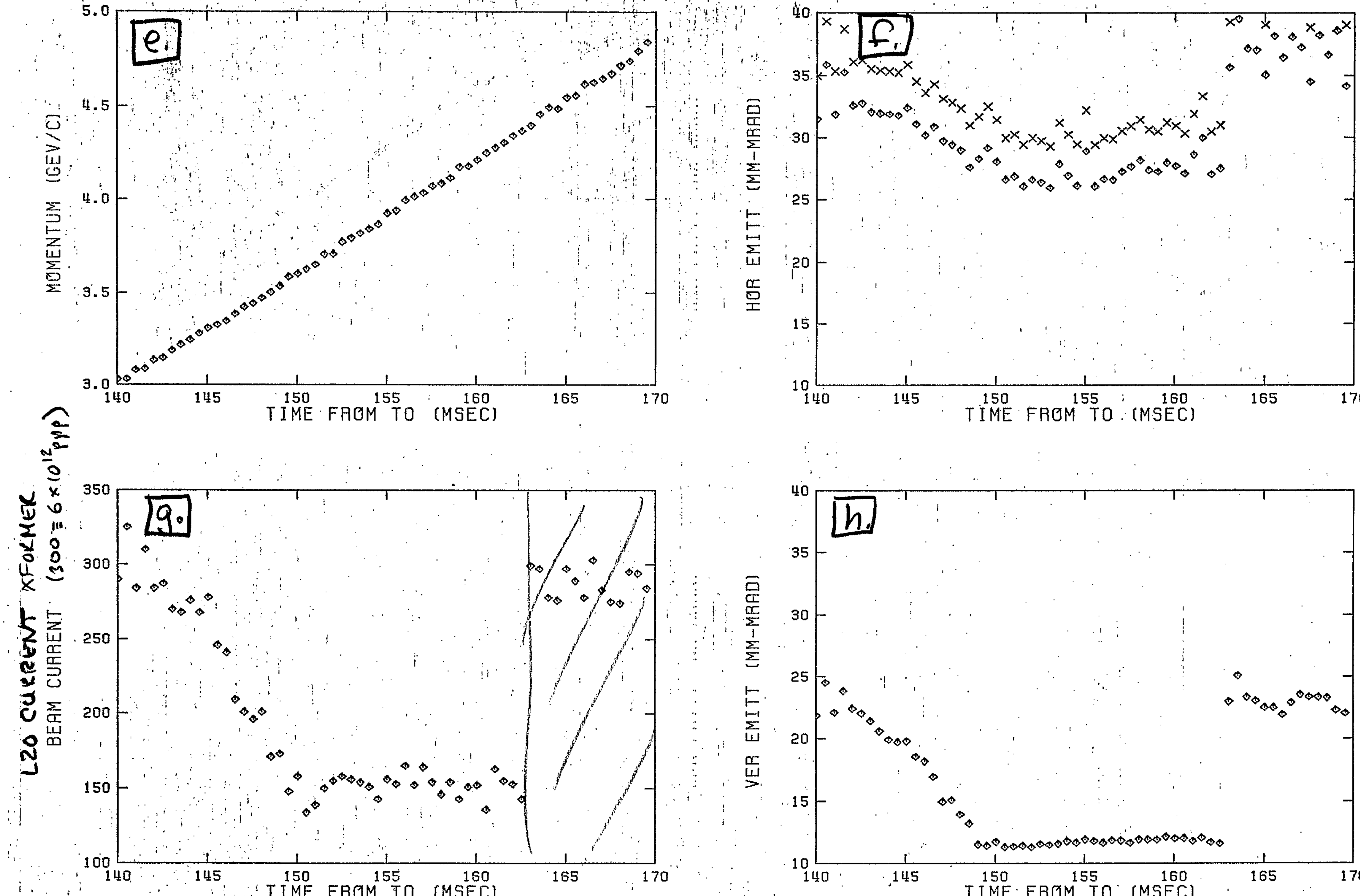

Fig. 1 (continued)

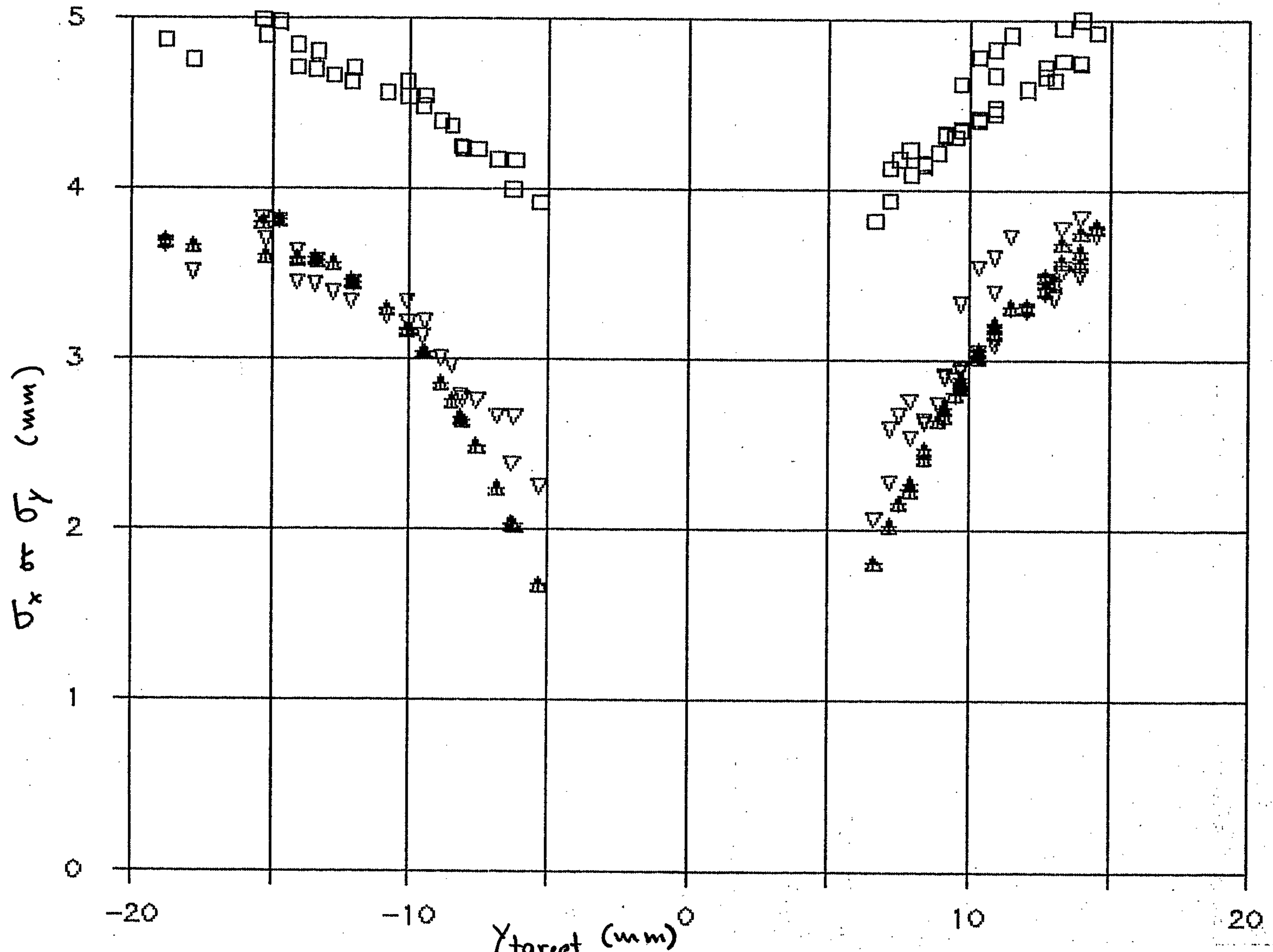

Fig.7 IPM size of "shaved" beam.

△ vertical □ horizontal

▽ horizontal, corrected for $\Delta p/p$: $\sigma^2_{corr.} = \sigma^2 - (x_p \cdot \frac{\Delta p}{p})^2$

$x_p = 1.9m$ $\frac{\Delta p}{p} = 0.17\%$

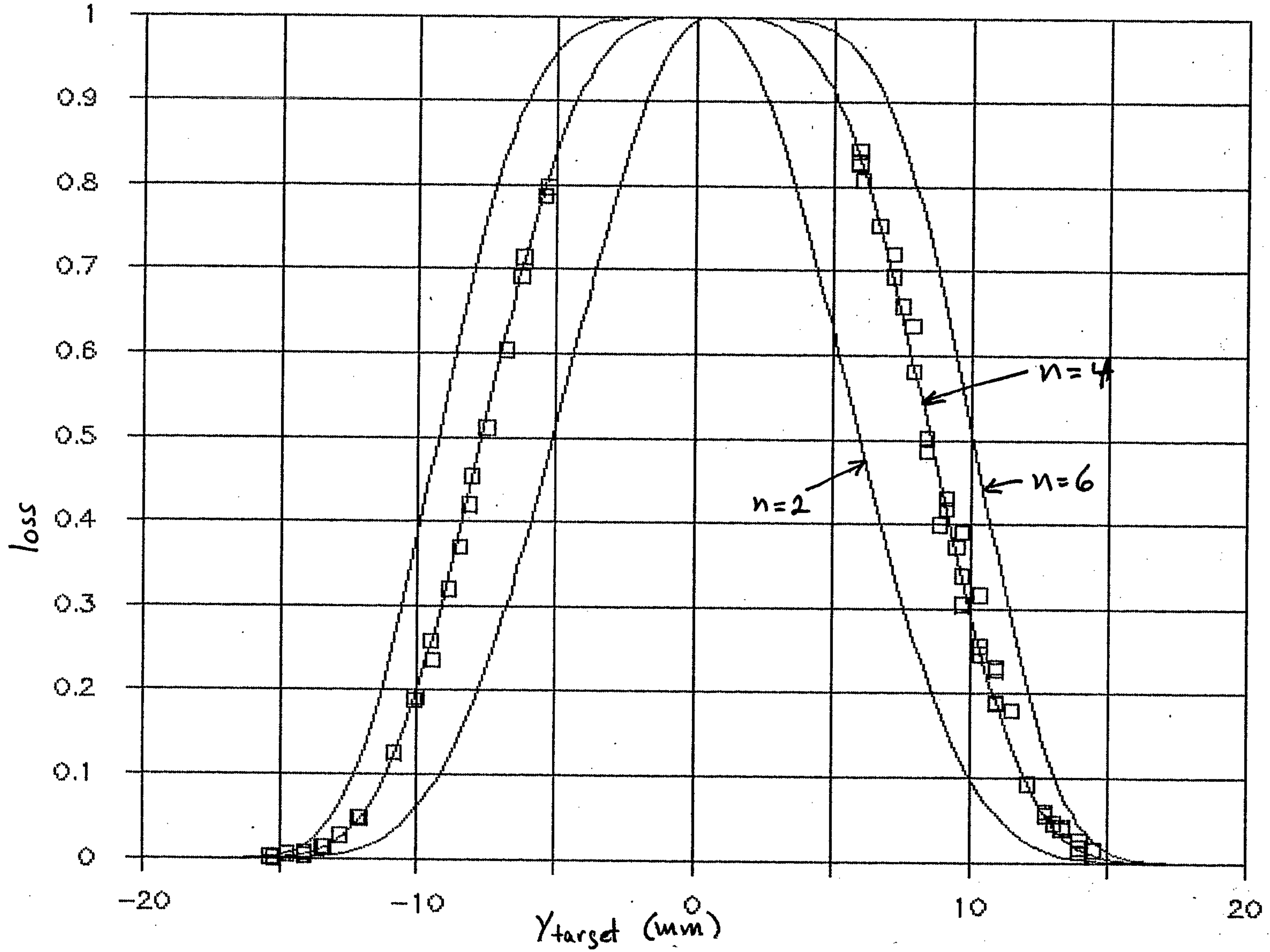

Fig. 6 Models with suppressed tails.

$f_n(r) = K_n r^{n-1} e^{-(r^2/2 + a r^6)}$; $a = .0035$; $Y = (\pm \sigma r + y_0)$

The "sigma" σ is the same for each curve, and has been adjusted to match the data for the 4-dimensional curve.

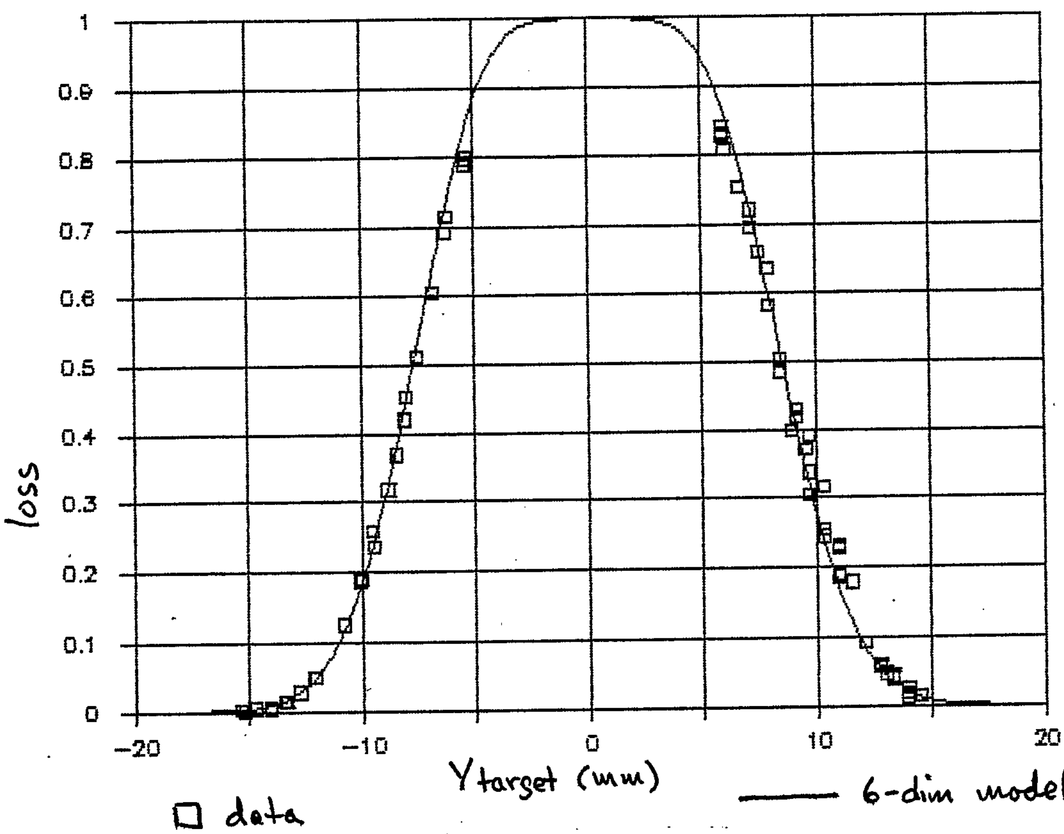

Fig. 5. 6-dim model with $\sigma = 3.5$ mm.

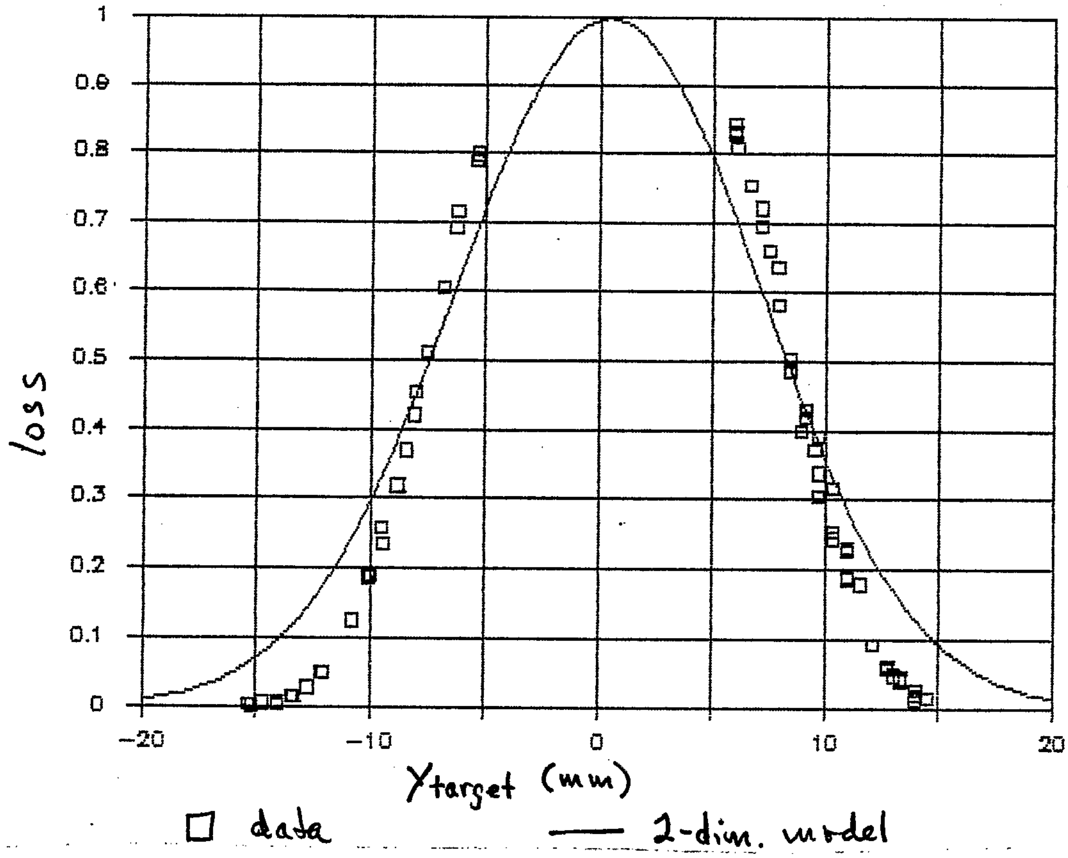

Fig. 3 Loss data and 2-dim. model $\int_{r_t}^{\infty} dr\ K_2 r e^{-r^2/2}$
where $y = (\pm\sigma r + y_0)$, $y_0 = .4$ mm, $\sigma = 6.68$ mm

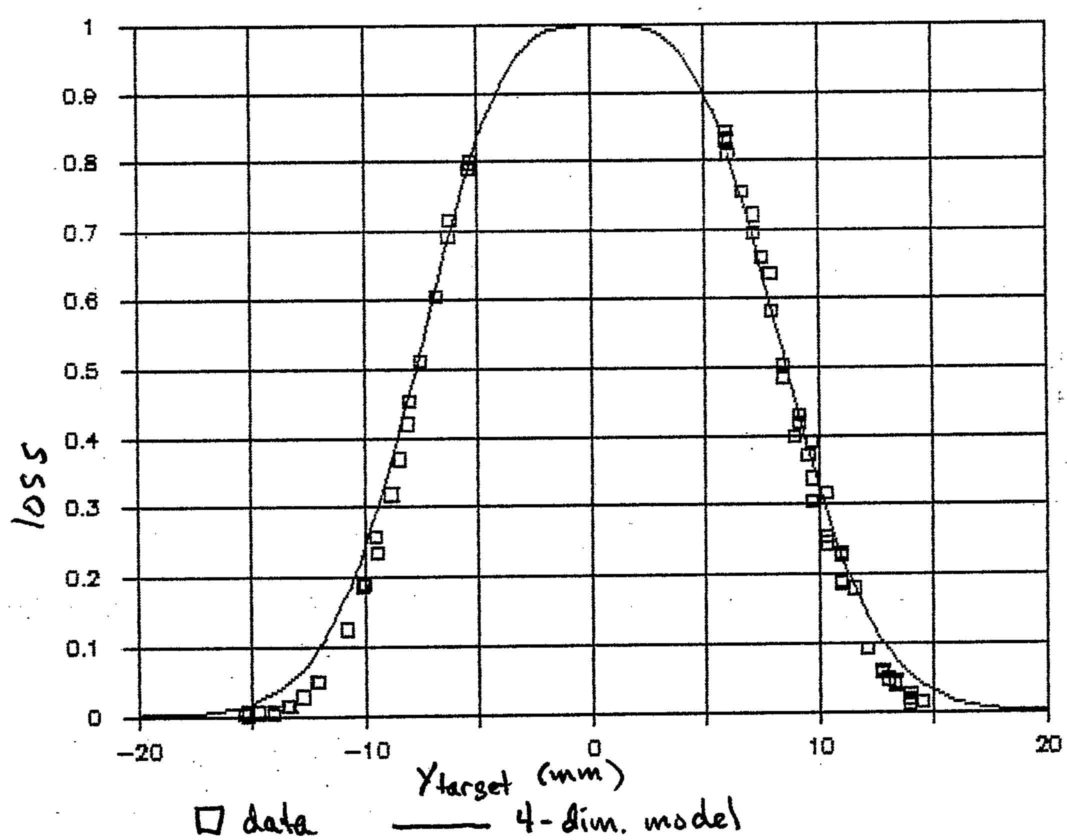

Fig. 4 4 dim. model $\int_{r_t}^{\infty} dr\ K_4 r^3 e^{-r^2/2}$
$\sigma = 4.45$ mm

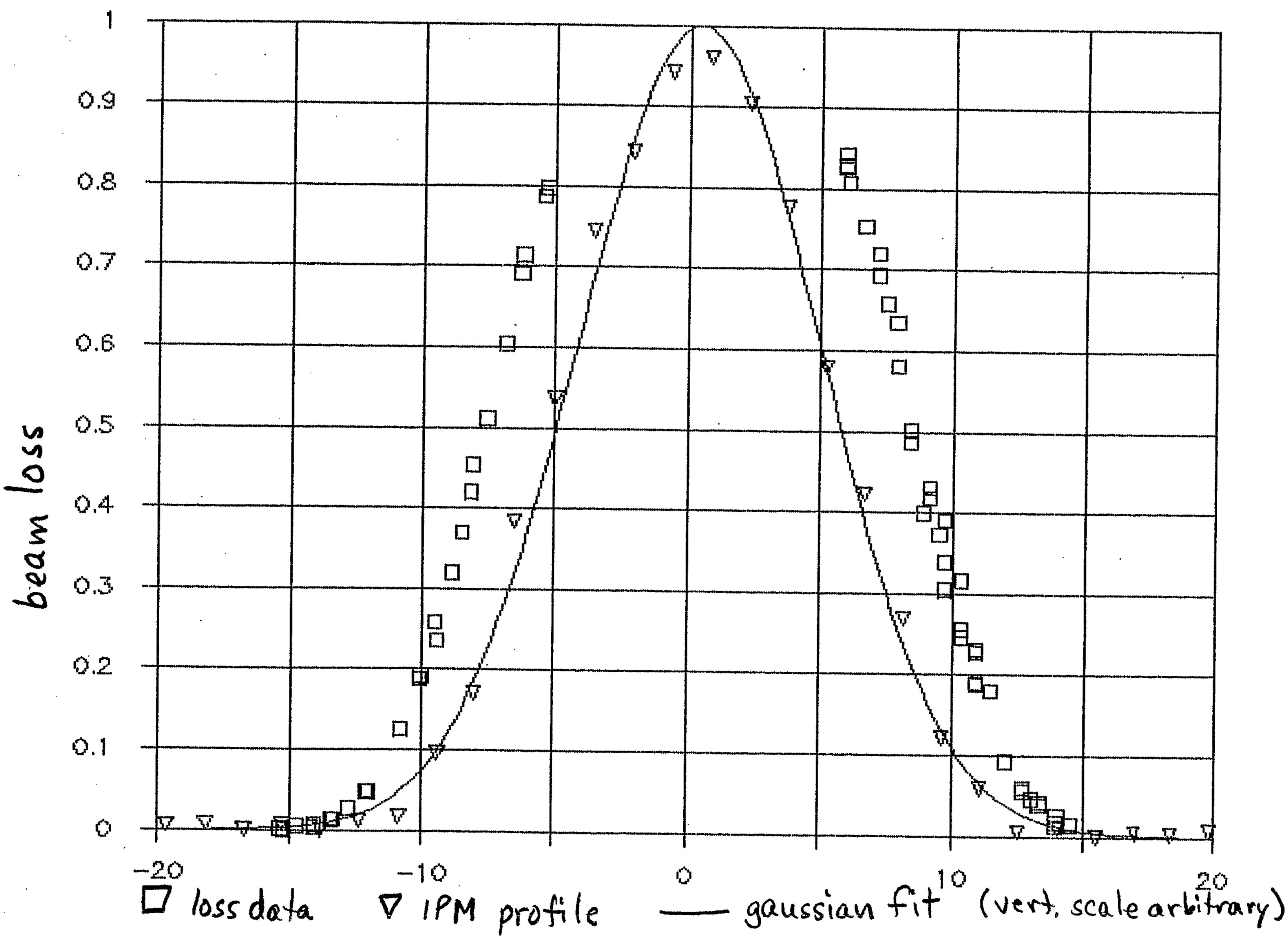

Fig. 2 Target beam loss and IPM profile