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Booster Studies of Au+15 Losses

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AGS Complex Machine Studies (AGS Studies Report No. 317) Booster Studies of Au^{+15} Losses
Study Period: September 15 and 22, 1994
Participants: M. Blaskiewicz and L. Ahrens
Reported by: M. Blaskiewicz
Machine: Booster
Beam: Au (+15) and Au (+14)
Tools: LeCroy Oscilloscope
Aim: To quantify losses

A beam of Au (15+) ions (neutral gold minus 15 electrons) is injected into the Booster. Normally there are about 10^9 ions injected into the ring but this number was varied between 1.0×10^8 and 2.0×10^9 for study purposes. The initial kinetic energy is 220MeV per ion which corresponds to 1 MeV/nucleon or a velocity of $v = 0.045c$. The beam pipe has an average radius of $r = 7$cm the synchrotron has a circumference of $C = 201.8$m with a gas volume of $V = 3.\text{m}^3$. Under standard operating conditions the pressure of the backround gas is about $2. \times 10^{-11}$Torr. At 300K this corresponds to 2×10^{12} particles (electrons+ions+neutrals) of residual gas in the ring. The ions are captured in 9 RF buckets resulting in 9 bunches. The density distribution within the bunches is complicated owing to filamentation of the phase space, but the envelope of the distribution is roughly a 3D Gaussian with horizontal and vertical standard deviations of $\sigma_H \approx \sigma_V \approx 1$cm and a longitudinal standard deviation $\sigma_S = 5$m, at injection. The bunches are accelerated to a top kinetic energy of 13 GeV in 1 s. During this process the transverse standard deviations decrease by a factor of 2.7 and the longitudinal standard deviation decreases by a factor of 1.6 due to the near conservation of adiabatic invariants. During acceleration many of the ions are lost. To study the loss mechanism "porches" at various energies were included in the machine cycle. (A porch is an interval during which the magnetic field is held constant so that the beam has a fixed velocity.) The data obtained were digitized readouts of the current transformer, a data sample every 0.2ms. These files were smoothed and decimated by a factor of ten yielding 1000 data points over the trace interval of 2 seconds. A conversion factor of 44.6×10^6charges/volt was assumed. Table 1 gives a summary of the porch data. The first column in Table 1 is a file identifier. The prefix "s" corresponds to data taken on 15 Sept 94. A "g" corresponds to the subset of these data taken during the vacuum study. A "t" corresponds to data taken on 22 Sept 94. A "u" corresponds to the subset of these data taken when the magnet cycle was modified to include an interval of reduced dwell value. The second column in Table 1 is the number of ions measured at the beginning of the cycle using the current transformer in units of 10^8. The next 3 columns are parameters characterizing the current transformer trace during the porch. During an interval of duration τ (last column) the function

$$\ln(N(t)) = \ln(N_1) + a_1 t + a_2 t^2 \tag{1}$$

was fit to the natural log of the number of particles obtained from the current transformer trace and time t was measured from the beginning of the fit interval. For purely exponential decay $-a_1$ is the loss rate (inverse lifetime). A non-zero value of a_2 indicates non-exponential behavior. Values of a_2 which are identically zero were inserted by hand (eg. only the parameters N_1 and a_1 were used in the fit). This was done for noisy data and during the gas pressure study. Column 6 is relevant for the "cooling" studies when the beam was turned off for a few cycles and then turned back on. A value of 1 in column 6 corresponds to the first shot after cooling, a 2 to the second etc. A value of 99 in column 6 corresponds to equilibrium. Column 7 gives the ion momentum times the speed of light in GeV. Column 8 gives the gas pressure in units of 10^{-11}Torr. Column 9 gives the charge of the ion and column 10 gives the duration of the fitting interval used to obtain the parameters that characterize the current transformer trace. Plots 1 through 4 show the average loss rate $= -(a_1 + a_2 * \tau)$ as a function of N_0, the number of ions just after injection for charge state 15 and various values of ion momentum. No significant difference between the loss rates for the normal dwell and the reduced dwell values were observed, only the normal dwell values are plotted. In addition to fitting Eq 1 the model equation

$$\frac{dN}{dt} = -\alpha N - \beta N^2 \tag{2}$$

was considered, where α and β correspond to the coefficients of the first and second order processes, respectively and n is the number of ions in the ring as bewfore. Physical mechanisms for α include residual gas scattering. For β processes such as ion-ion collisions would contribute. However, this particular effect is unlikely since the loss was not affected by turning off the RF on the porch. Integrating Eq 2 yields

$$N(t) = \frac{N_1}{1 + (1 + \beta N_1/\alpha)(\exp(\alpha t) - 1)} \tag{3}$$

where t is measured from the beginning of the fit interval. Eq 3 was fit to the current transformer data using non-linear least squares in a variety of ways. Initially N_1, α and β were allowed to vary from one data set to the next. In all cases the fit looked good in the sense that the curve went through the data points. However, for some of the data the best fit had negative values of α or β, which the author has been unable to assign a physical meaning to.

Next, the data were broken into subsets of constant momentum and charge state. For each of these subsets the value of α was set to zero and β was varied. For some of the data the fit looked OK but for much of the data the best fit had a significantly larger curvature than the data; initial loss rates were smaller than the best fit values while final loss rates were larger than the best fit values. Setting $\beta = 0$ and fitting for α had a tendency to display the reverse effect with the initial loss rates larger than the best fit values and visa versa. As a working hypothesis I assumed that the value of β should have a tendency to be universal, while α is a reasonable parameter in which to incorporate the "memory effect". The memory effect can be seen in Figure 5, where files t074, t075 and t078 are plotted. The cycle following a period of no beam results in the largest intensity at the end of the cycle while the equilibrium condition results in the smallest. The only cycle to cycle effect I know of would involve enhanced quantities of residual gas, which manifests as a first order effect if the rise time for the density of residual gas is longer than the decay time of the data. However, since it is possible that residual gas build-up occurs concurrently with beam loss, the best fit value of β could also be affected. In fact, for the traces in Fig 5. the best fit values of α and β are (1.71, 0.014), (2.09, 0.023), and (2.58, 0.046) going from small to large losses, respectively. While the values of α and β have statistical errors of order 0.01 and 0.005, respectively the absolute value of the root mean square difference between the data and the fit was not too sensitive to the value of β. Allowing β to float for the three files resulted in an rms of 8.4×10^6 ions while setting $\beta = 0$ resulted in an rms of 9.8×10^6. The smallest rms value for fixed β occured for $\beta \approx 0.02$ and was 8.8×10^6, a 5% increase in rms over the minimum value. Additionally, fitting a function of the form

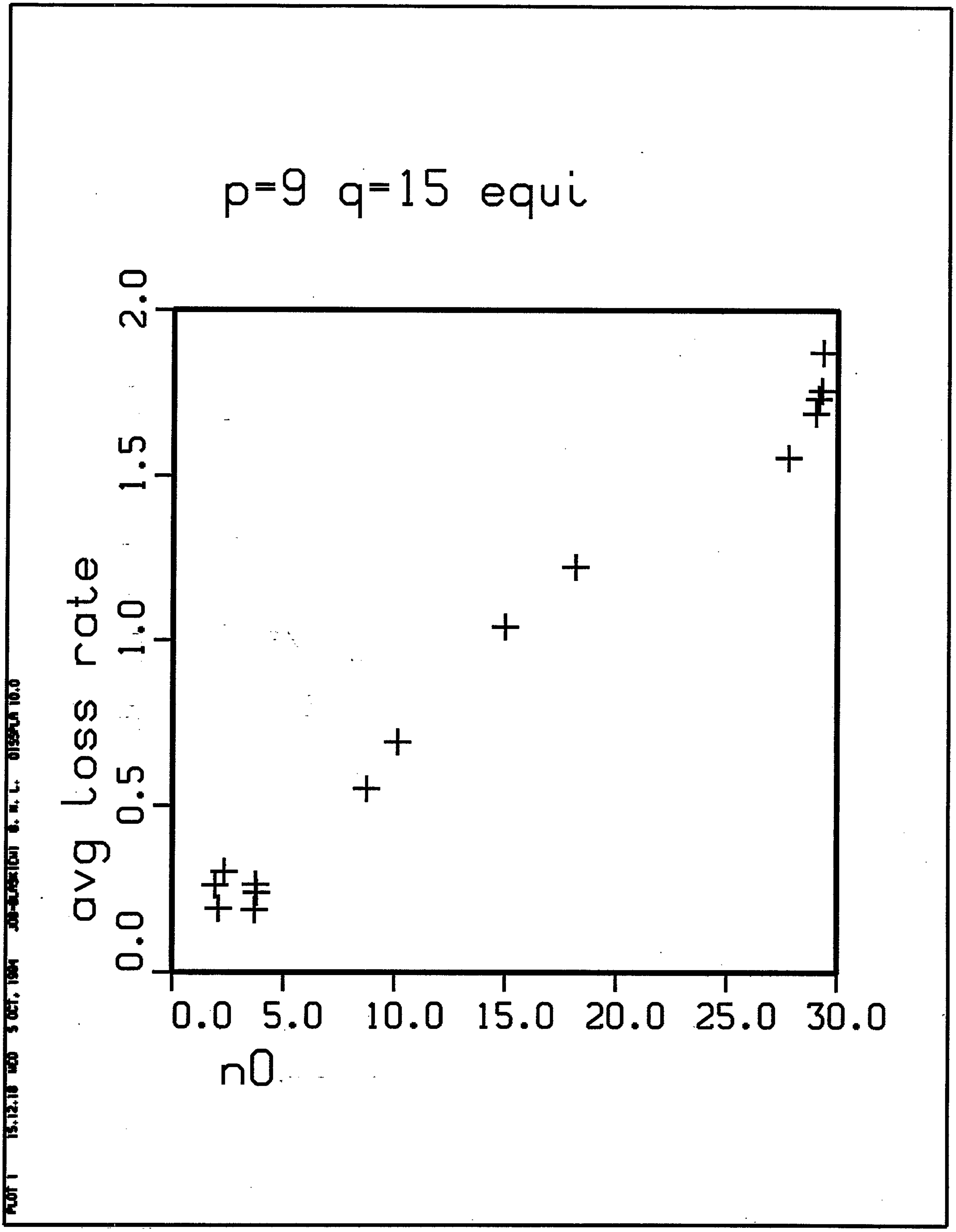
$$N(t) = N_0 e^{a_1 t + a_2 t^2} \tag{4}$$

to the same traces resulted in an average rms of 7.7×10^6 which is 9% smaller than the best result using Eq 3, which argues that the fits using Eq 1 yield about as much information as one can extract from the data.

Table 1) Summary of current transformer data

file	N0	N1	a1	a2	pulse	pc	pg	charge	tau	
s002	12.03	6.07	-1.83	-0.26	99	30	2	15	0.6	
s003	11.87	6.09	-1.91	0.07	99	30	2	15	0.6	
)5	14.84	5.92	-2.63	0.32	99	30	2	15	0.6	
s006	19.19	5.81	-3.40	0.74	99	30	2	15	0.6	
s007	19.81	4.05	-3.99	1.11	99	30	2	15	0.6	
s008	17.46	5.38	-2.73	0.64	3	30	2	15	0.6	
s009	17.98	7.48	-2.04	0.30	1	30	2	15	0.6	
s010	5.47	4.00	-0.78	0.00	99	30	2	15	0.6	
s011	3.36	2.46	-0.40	0.00	99	30	2	15	0.6	
s012	1.91	1.56	-0.30	0.00	99	30	2	15	0.6	
s013	4.20	3.37	-0.26	0.00	99	60	2	15	0.4	
s014	6.62	4.75	-0.44	0.00	99	60	2	15	0.4	
s015	14.21	5.85	-1.10	-0.08	99	60	2	15	0.4	
g016	14.24	4.12	-1.50	0.00	99	60	10	15	0.4	
g017	14.26	5.72	-1.17	0.00	99	60	2	15	0.4	
g018	13.73	4.53	-2.66	0.00	99	30	10	15	0.4	
g019	13.74	5.41	-2.49	0.00	5	30	10	15	0.4	
g020	13.70	7.09	-1.82	0.00	1	30	10	15	0.4	
g021	13.56	5.58	-2.39	0.00	5	30	10	15	0.4	
g022	13.54	7.66	-1.59	0.00	1	30	10	15	0.4	
g025	13.33	10.88	-12.35	0.00	99	30	200	15	0.2	
g026	13.64	12.77	-2.25	0.00	99	30	10	15	0.2	
g028	13.08	11.34	-7.38	0.00	1	30	200	15	0.2	
g029	13.13	11.64	-9.14	0.00	13	30	200	15	0.2	
g030	13.18	11.94	-3.32	0.00	99	30	50	15	0.2	pg=?
g031	13.12	12.55	-1.86	0.00	99	30	2	15	0.2	
s032	14.11	5.39	-1.25	0.08	99	60	2	15	0.4	
34	18.52	4.94	-1.51	0.32	99	60	2	15	0.4	
35	17.58	7.41	-0.95	0.19	1	60	2	15	0.4	
s036	10.43	5.66	-0.73	-0.06	99	60	2	15	0.4	
s037	10.60	6.66	-0.48	-0.08	1	60	2	15	0.4	
s039	6.57	4.50	-0.32	-0.28	99	60	2	15	0.4	
s040	6.44	4.81	-0.27	-0.08	1	60	2	15	0.4	
s041	3.81	2.94	-0.20	-0.10	99	60	2	15	0.4	
t004	17.90	14.40	-1.26	0.44	1	9	2	15	0.8	
t005	18.16	13.94	-1.52	0.37	99	9	2	15	0.8	
t007	18.54	13.87	-1.27	0.34	1	9	2	15	0.8	
t009	16.95	11.12	-0.55	-0.01	1	9	2	15	0.8	
t010	17.64	13.70	-1.20	0.37	1	9	2	15	0.8	
t011	17.23	13.47	-1.20	0.46	1	9	2	15	0.8	
t012	29.34	18.62	-2.48	0.76	99	9	2	15	0.8	
t013	21.38	15.18	-1.56	0.55	1	9	2	15	0.8	
t014	29.78	18.23	-1.93	0.76	1	9	2	15	0.8	
t015	28.20	17.00	-1.35	0.26	1	9	2	15	0.8	
t016	27.77	16.45	-1.62	0.08	99	9	2	15	0.8	
t017	15.00	11.70	-1.25	0.26	99	9	2	15	0.8	
t018	10.14	8.78	-0.87	0.22	99	9	2	15	0.8	
t019	9.61	8.29	-0.69	0.21	1	9	2	15	0.8	
t020	8.75	7.72	-0.56	0.01	99	9	2	15	0.8	
t021	3.75	3.37	-0.27	0.01	99	9	2	15	0.8	
t022	3.79	3.49	-0.23	-0.01	99	9	2	15	0.8	
t023	3.79	3.32	-0.39	0.18	1	9	2	15	0.8	
t024	3.70	3.42	-0.33	0.18	99	9	2	15	0.8	
5	2.08	1.75	-0.27	0.10	99	9	2	15	0.8	
t026	1.93	1.79	-0.50	0.30	99	9	2	15	0.8	
t027	2.34	1.94	-0.62	0.40	99	9	2	15	0.8	
t028	29.28	17.65	-2.67	1.14	99	9	2	15	0.8	
t029	29.14	16.45	-2.55	1.02	99	9	2	15	0.8	

t030	29.12	17.79	-2.17	1.03	1	9	2	15	0.8
t031	29.01	16.35	-2.49	1.00	99	9	2	15	0.8
t032	28.70	17.42	-2.33	1.14	1	9	2	15	0.8
t033	43.32	21.59	-3.83	1.53	99	9	2	14	0.8
[illegible]4	42.09	23.72	-3.00	1.33	1	9	2	14	0.8
t036	38.15	20.54	-2.95	1.22	1	9	2	14	0.8
t037	33.76	18.57	-2.83	1.00	99	9	2	14	0.8
t038	25.46	16.21	-2.21	0.74	99	9	2	14	0.8
t039	25.62	15.72	-2.30	0.86	99	9	2	14	0.8
t040	17.83	13.40	-1.47	0.33	99	9	2	14	0.8
t041	17.96	13.50	-1.32	0.42	1	9	2	14	0.8
t043	10.67	8.71	-0.87	0.17	99	9	2	14	0.8
t044	10.69	9.00	-0.98	0.41	1	9	2	14	0.8
t045	7.82	6.60	-0.68	0.12	99	9	2	14	0.8
t046	7.43	6.38	-0.54	0.04	99	9	2	14	0.8
t047	5.51	4.81	-0.49	0.08	99	9	2	14	0.8
t048	5.37	4.82	-0.38	-0.03	99	9	2	14	0.8
t049	5.23	4.56	-0.34	0.00	1	9	2	14	0.8
t050	5.30	4.60	-0.31	-0.17	99	9	2	14	0.8
t051	3.49	2.89	-0.33	0.01	99	9	2	14	0.8
t052	3.43	2.90	-0.53	0.34	99	9	2	14	0.8
t053	2.58	2.20	-0.01	-0.20	99	9	2	14	0.8
t054	2.26	1.19	-0.01	-0.18	99	9	2	14	0.8
u055	15.65	10.81	-1.50	0.50	99	9	2	15	0.8
u056	15.35	11.39	-1.54	0.58	99	9	2	15	0.8
u057	14.70	10.80	-1.21	0.44	1	9	2	15	0.8
u058	15.42	11.42	-1.56	0.61	99	9	2	15	0.8
u059	21.59	13.70	-2.21	1.00	99	9	2	15	0.8
u060	21.63	14.53	-1.99	0.92	1	9	2	15	0.8
[illegible]1	22.75	14.20	-2.23	0.95	99	9	2	15	0.8
[illegible]2	8.19	7.40	-0.60	0.11	99	9	2	15	0.8
u063	8.16	7.72	-0.51	0.11	1	9	2	15	0.8
u064	8.32	7.38	-0.47	-0.02	99	9	2	15	0.8
t066	7.97	6.55	-0.69	-0.15	99	15	2	15	0.8
t067	11.16	8.57	-1.18	-0.21	99	15	2	15	0.8
t068	11.25	9.38	-0.56	-0.22	1	15	2	15	0.8
t069	17.25	11.49	-2.34	0.12	99	15	2	15	0.8
t070	17.14	12.79	-1.00	-0.36	1	15	2	15	0.8
t071	21.81	12.78	-3.30	0.67	99	15	2	15	0.8
t072	21.81	13.34	-3.25	0.59	99	15	2	15	0.8
t073	21.64	14.86	-1.68	-0.17	1	15	2	15	0.8
t074	22.71	13.01	-3.28	0.69	99	15	2	15	0.8
t075	22.45	14.38	-1.94	0.18	1	15	2	15	0.8
t078	22.10	13.79	-2.48	0.34	2	15	2	15	0.8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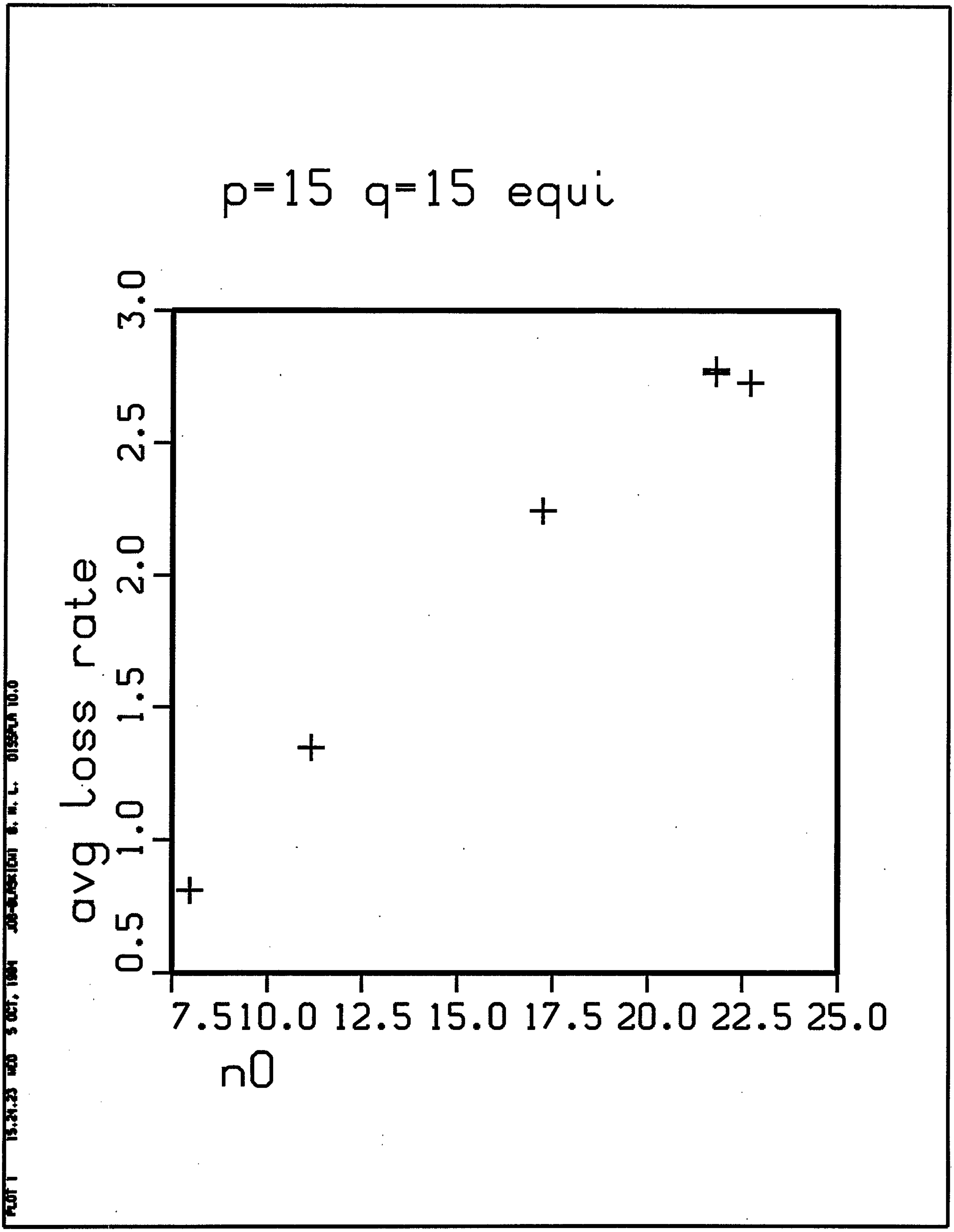
0.5
1.0
1.5
2.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
n0

Figure 1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1.0
1.5
2.0
2.5
3.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
n0

Figure 2

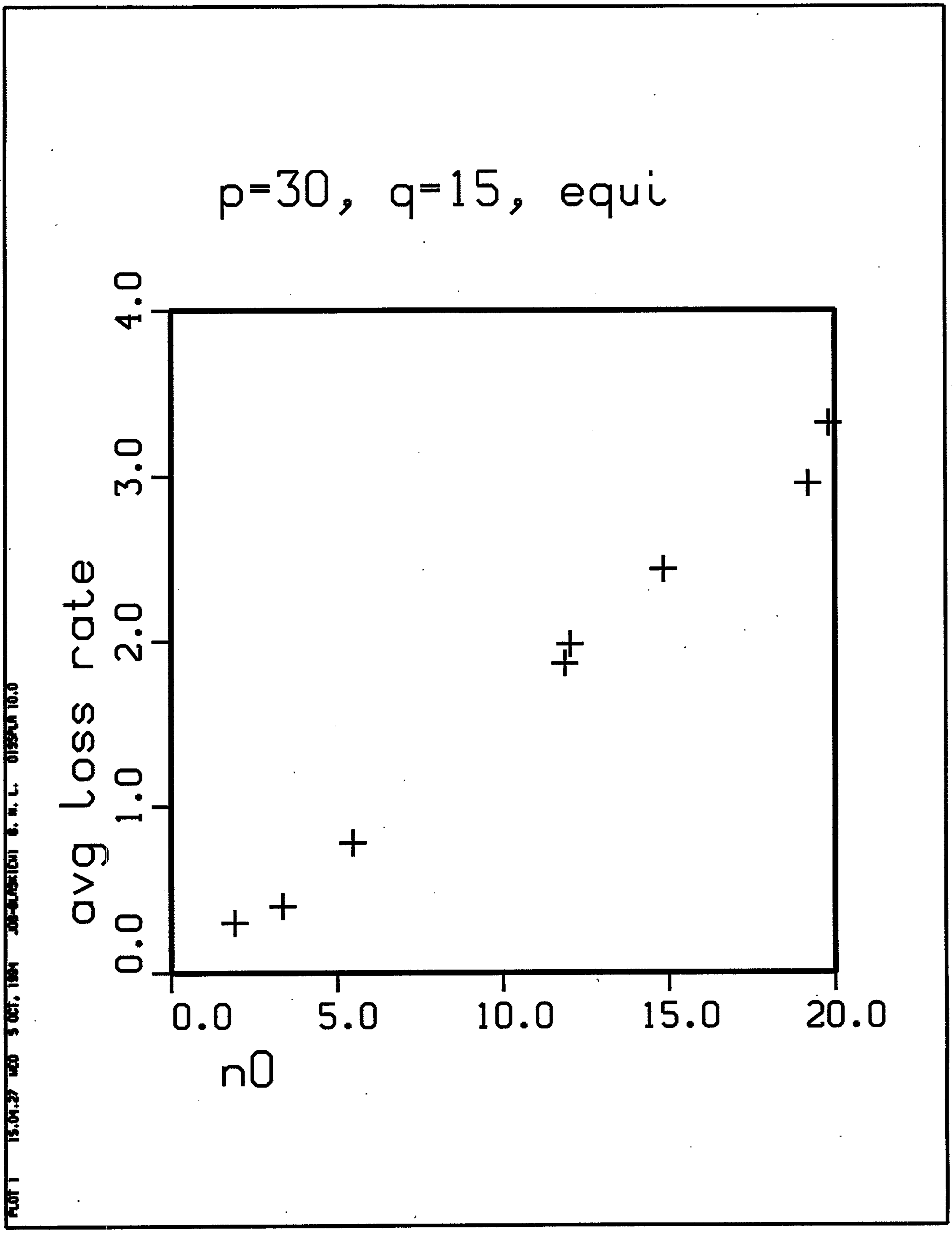
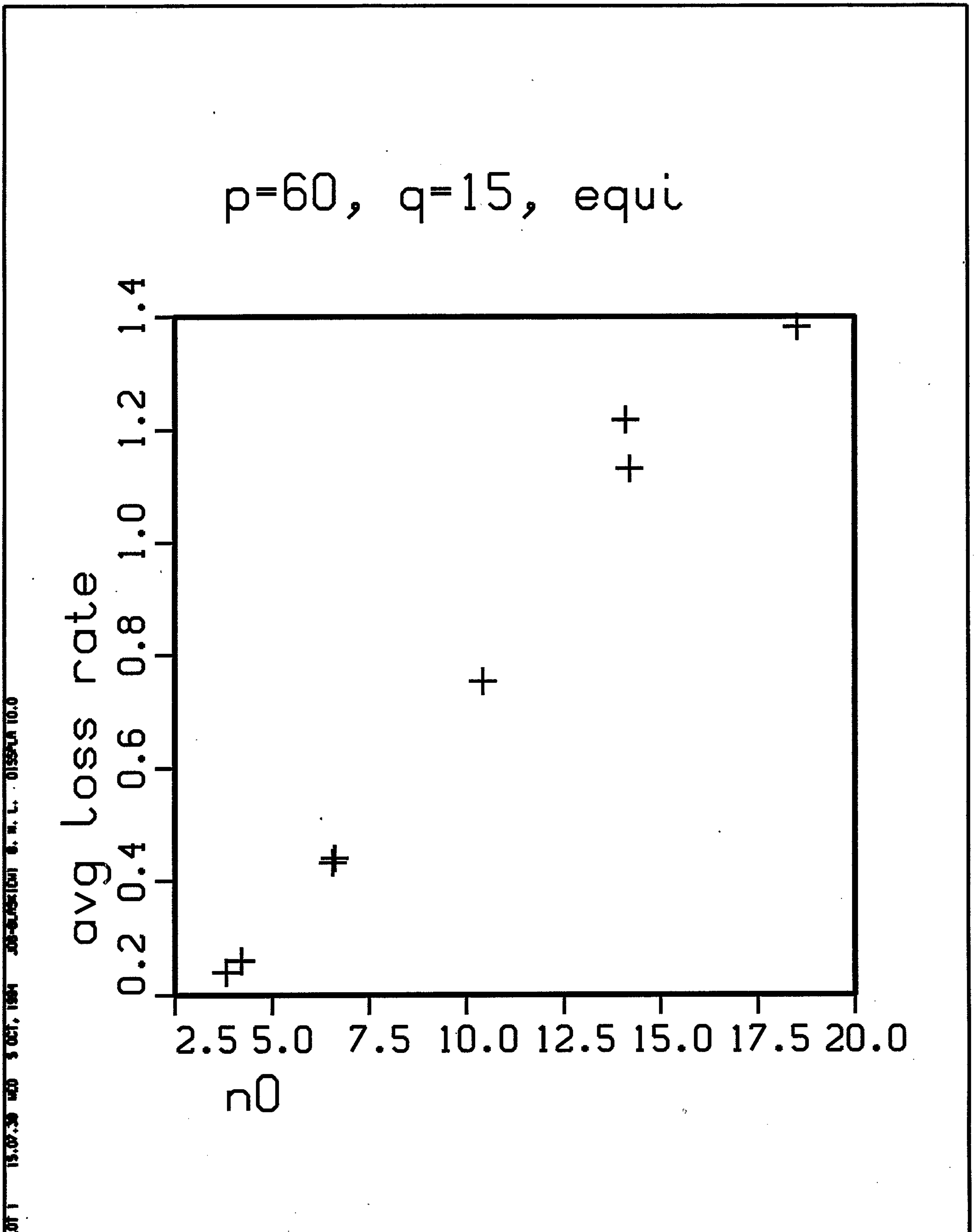


Figure 3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avg loss rate
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2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0
n0

Figure 4

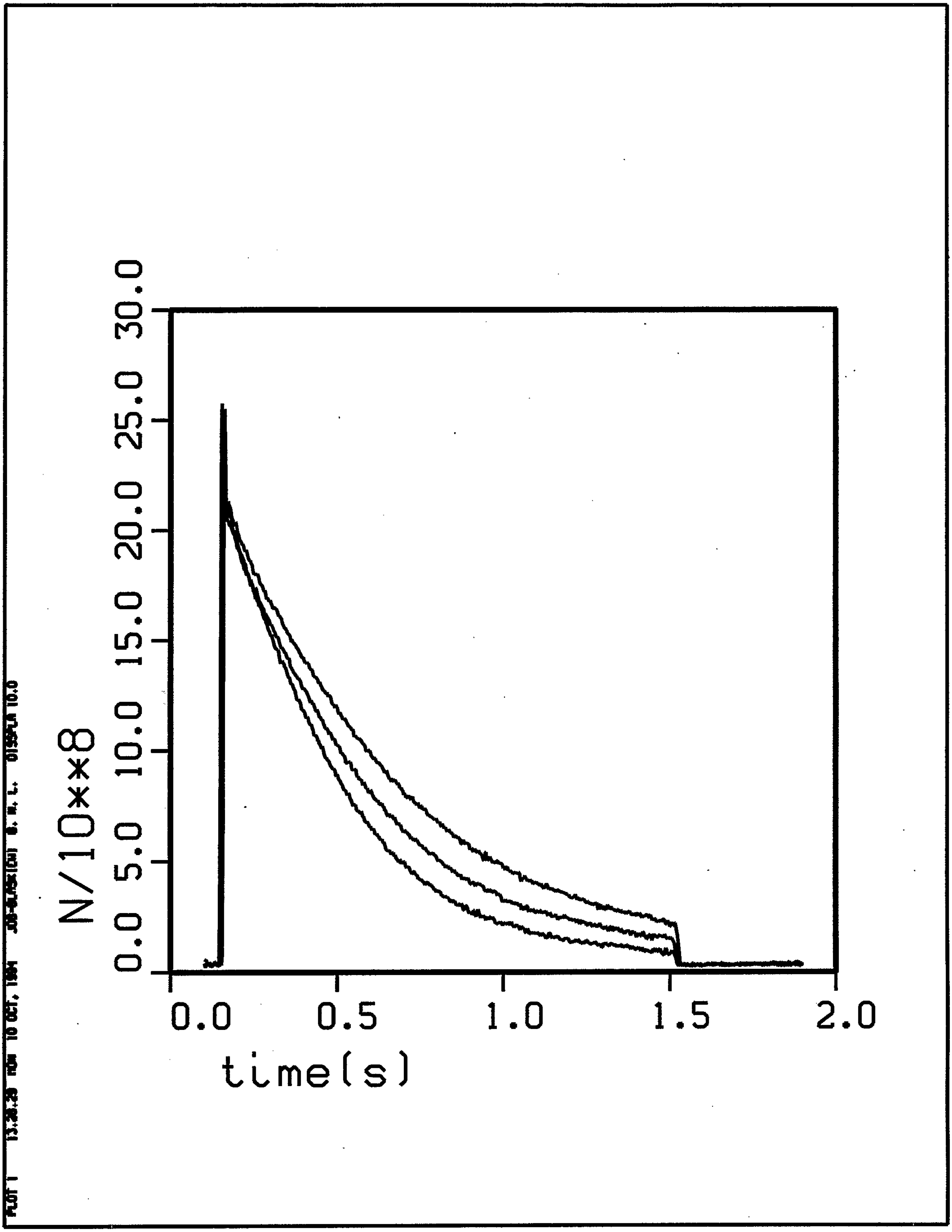

Figure 5