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Collider Accelerator Department

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I. Introduction

This note briefly describes calculations made to determine the "performance" of the Booster ejection system and internal dump as a function of characteristics of the beam kickers. The motivation for the calculations is concern about radiation problems. In the case of the ejection septum, 1% loss has been assumed(1) in an area which is difficult to shield (Bldg. 914), so that explicit verification of that assumption was considered desirable. In the case of the dump, the focus of concern was the kicker rise time; a fast kicker is inherently more efficient - more effectively confining radiation products within the dump or region close to the dump - but is more costly. In both cases, the high intensity (unpolarized) proton beam dominates the radiation burden; no attention is given to heavy ions in this note.

II. Method of Calculation

A Monte Carlo tracking program was written to perform the calculations described below. The approximation of a linear machine was always made. In such a machine, the χ coordinate of the i-th particle as a function of longitudinal position s is given by:

$$X(i,s) = a_i \cdot \sqrt{\beta(s)} \cdot \cos(\psi(s) + \delta_i) + \chi(s) \cdot \Delta p/p(i)$$

"Transport" of a specific orbit from s_1 to s_2 is accomplished by a simple change of lattice functions: $\beta(s_1) \rightarrow \beta(s_2)$; $\psi(s_1) \rightarrow \psi(s_2)$, $\chi(s_1) \rightarrow \chi(s_2)$ [here ψ is the lattice phase and χ the dispersion function]. A change of direction at a point results in a new orbit, i.e., new values of amplitude a_i and phase δ_i. The conditions $X_i = X_j$ and $X'_i - X'_j$ = kick give the new amplitude and phase, where $X' = dx/ds$. In the case of the dump calculations, an orbit impinging on the dump is tracked through the dump material. If it interacts, the orbit is abandoned. If it re-emerges before interacting, new values of a_i, δ_i and $\Delta p/p$ (i) are calculated and "transport" is resumed.

The key quantities are the population distributions of the amplitude (a) and momentum bite ($\Delta p/p$), and the time-function of the kick. Each of these is allowed to vary, to greater or lesser extend, and results given as a function of these variables.

III. Fixed Parameters

The lattice functions were taken from Appendix A of the Booster Project Design Manual (2) which is reproduced here as Fig. 1. All orbits "start" at the position of the dump kicker which is treated as a point in the middle of the drift region downstream of element number 15 (see Fig. 1) in the "D" superperiod. Other "special" positions - which intrude into the normal vacuum chamber aperture - include the upstream edges of the dump (D superperiod) and ejection septum (F superperiod), which are taken to be 70 cm. downstream of element number 34; the upstream edge of the heavy ion injection septum, taken to be 70 cm. downstream of element number 15 in the "C" superperiod; and the stripping foil, assumed 30 cm. downstream of element 29 in the "C" superperiod.

A number of other positions are known to the program - including the position of maximum beta (horizontal) in each superperiod and a few positions in the region of the dump where an orbit "bump" is assumed to exist. Nominal values for the bump, treated as simple transverse orbit displacements, were supplied by E. Bleser(3). Besides the horizontal beta functions, lattice phase, dispersion and apertures for these positions, the only other data required is the machine tune (4.820) and the alpha function in the region of the dump.

IV. Kicker Function

Since the dump kicker/block are in the same positions as the ejection kicker/septum (except for the superperiod) many results nominally simulating the dump would apply to the septum. However, a significant difference is assumed in the kicker functions. In the case of the septum, a sine wave, synchronized to start at the end of one of the Booster bunches, rises to its peak value in a quarter period of 120 nsec. Thereafter, it oscillates with only a 2% decrease in amplitude. The dump kicker is much sloppier - with a variable quarter period (risetime), but a 20% decrease in amplitude.

V. Amplitude Function

The amplitude defined in Section II is the square root of the emittance. The amplitude is sampled from a 2-D Gaussian whose 1 sigma value is given by SQRT (A)/2.145 at 200 MeV where $A = 50 \times 10^{-6}$ m.rad, the design injection admittance of the Booster. This distribution gives 10% of the amplitudes greater than SQRT (A) as stated in the Booster Design Manual. The maximum value of the emittance, or its square root, the amplitude, is determined by some physical aperture. Normally, the assumption is made that strong X-Y coupling results in the dipole vertical opening (full width = 2.65 inches) serving as the horizontal aperture.(4) This gives, with the approximation that the vertical beta function at a dipole is 90% of the maximum beta, the condition that $A_{max} \cong 90.5 \times 10^{-6}$ m.rad (again at 200 MeV). For zero X-Y coupling, presumably an overly conservative assumption, the horizontal aperture limit would be set by the dump block. We assume here that the block has an aperture at x = 4.145 cm on the low momentum side and that this aperture shadows all others by ~ 3 mm. This would lead to a maximum injection amplitude corresponding to $A_{max} = 165 \times 10^{-6}$ m.rad. Although most calculations were done for the strong X-Y coupling assumption, results are also given below for the more conservative assumption. In all cases, the square of the amplitude is assumed to scale inversely with momentum.

VI. Momentum Bite

The RF bucket energy width given in the Booster Design Manual would correspond to a maximum momentum spread of $\Delta p/p = 0.4\%$. However, the longitudinal emittance does not fill the bucket so that the momentum spread is restricted to $\Delta p/p = 0.2\%$(5). The orbits are sampled uniformly in the momentum bite which is pessimistic.

VII. Loss on the Ejection Septum

The first step in this calculation was to scale the bump values such that 0.1% of the beam was observed to intercept the dump face. [The symmetry of the ejection septum and dump positions in the lattice allow calculations, though nominally done for the dump, to apply to the ejection septum. Scaling the bump values to "park" the beam near the edge effectively removes the lack of symmetry introduced by the 3 mm. aperture shadowing assumption mentioned in Section V]. The orbits are then kicked with the ejection kicker function described in Section IV and the distribution of x-positions on the entrance face of the dump observed. Since the effective width of the ejection septum is 1.0 cm (4), the amount of orbits within the first 1 cm represent beam lost in the ejection septum.

The results are shown in Figure 2 as a function of $\Delta p/p$ and kicker amplitude for the strong x-y coupling assumption. The Booster Design Manual value of a 5 mrd kick gives 1.3% loss at $\Delta p/p = 0.2\%$ in excellent agreement with the 1% loss assumption mentioned in the introduction. The value of 5.5 mrd is shown because the kicker strength is not limited by the high intensity protons, but by low intensity Au ions. A slightly higher kick strength, which is available for protons, clearly has a dramatic effect on beam loss. The limit to the kicker strength is likely set by beam loss on the opposite side of the septum magnet aperture. Although this has not been examined in detail, a cursory examination of the magnet aperture (whose dimension is determined largely by sagitta) would appear to allow a few tenths of a milliradium beyond the nominal value of 5 mrd.

If the pessimistic assumption of no x-y coupling is made (Section V), the 1.3% loss ($\Delta p/p = 0.2\%$) at 5.0 mrd increases to 3.6% and the 0.25% at 5.5 mrd increases to 0.60%. In view of the fact that the flat $\Delta p/p$ distribution is also pessimistic and that a few tenths of a milliradiun "extra" kick would appear feasible, the 1% loss assumption remains a reasonable expectation.

VII. Loss From the Dump

The differences in the simulation of the dump losses are twofold: (1) the "sloppier" kick function described in Section IV is used, and (2) the term "loss" does not refer to particles which intercept the dump, but to particles which out-scatter from the dump face without interacting. it is important to note that "loss" from the dump is not the same thing as dump "ineffeciency". The latter term is generally used to designate the amount of energy which is not maintained in the dump. This note does not address that question, which would require following the hadron cascade which results from interacting protons. An early consideration of that topic is addressed elsewhere.(6)

Figure 3 shows dump loss as a function of kicker rise time assuming the 5 mrd amplitude. Within the statistical accuracy of the calculation, 9000 orbits are tracked for each calculation - no difference is seen between the two amplitude cut-offs. At the 3 microsec value, 2 orbits (.02%) are lost on the ejection septum. For the shorter rise-times considered, the loss is "clean" in the sense that all loss occurs in the first dipole downstream of the dump. The results indicate that a kicker with a rise time close to the orbital period (729 nsec) should suffice.

VIII Conclusions

The calculations described here confirm that a 1% loss of the extracted proton beam on the ejection septum magnet is a reasonable estimate. If the assumption of strong horizontal - vertical coupling is confirmed in practice, significantly less loss may be achievable. The calculations also show that a dump kicker as slow as several revolution periods still serves to confine radiation to the region of the dump assuming the dump face "shadows" all other apertures by 3 mm.

References

1. "Preliminary Safety Analysis Report", AGS Booster Project, 12/1/87.
2. "Booster Design Manual - Revision 1", 1/12/89.
3. E. Bleser, private communication.
4. Y. Y. Lee, private communication.
5. S. Y. Lee, private communication.
6. A. J. Stevens, "Conceptual Design of the Booster Beam Dump", AD Booster Tech. Note 117, 4/21/88.

APPENDIX A. BOOSTER LATTICE RUN AND PLOT

Table A-1. List of Booster parameters at Qx=4.820, Qy=4.830: zero chromaticity and no eddy current sextupoles.

Num	Name	L(m)	Bend(rad)	(1/m2)*	bx(m)	Xp(m)	dQx	by(m)	dQy	S(m)
1	QD	0.251875		0.57541623	3.789	0.5462	0.011	13.157	0.003	0.2519
2	S30	0.300000			4.183	0.5654	0.023	12.041	0.007	0.5519
3	BEND	2.400000	0.17453293		9.,47	0.9184	0.085	5.413	0.055	2.9519
4	S70	0.400000			11.655	1.0790	0.096	4.247	0.078	3.6519
5	SF	0.000000		-0.1821779	11.655	1.0790	0.096	4.247	0.078	3.6519
6	S30	0.300000			12.700	1.1478	0.099	3.853	0.090	3.9519
7	QF	0.251875		-0.55821116	13.158	1.1850	0.103	3.703	0.101	4.2037
8	QF	0.251875		-0.55821116	12.705	1.1804	0.106	3.853	0.111	4.4556
9	S30	0.300000			11.665	1.1498	0.110	4.247	0.123	4.7556
10	BEND	2.400000	0.17453293		5.266	1.0982	0.159	9.687	0.184	7.1556
11	S70	0.400000			4.107	1.1394	0.183	12.041	0.194	7.8556
12	SD	0.000000		0.2949544	4.107	1.1394	0.183	12.041	0.194	7.8556
13	S30	0.300000			3.720	1.1571	0.195	13.157	0.198	8.1556
14	QD	0.251875		0.57541623	3.575	1.1932	0.206	13.644	0.201	8.4075
15	QD	0.251875		0.57541623	3.731	1.2729	0.217	13.157	0.204	8.6594
16	S340	0.700000			12.179	2.6562	0.301	4.247	0.279	12.0594
17	SF	0.300000		-0.1821779	12.179	2.6562	0.301	4.247	0.279	12.0594
18	S30	0.300000			13.335	2.7782	0.305	3.853	0.291	12.3594
19	QF	0.251875		-0.55821116	13.866	2.8311	0.308	3.703	0.302	12.6113
20	QF	0.251875		-0.55821116	13.435	2.7839	0.311	3.853	0.313	12.8631
21	S30	0.300000			12.389	2.6686	0.315	4.247	0.324	13.1631
22	BEND	2.400000	0.17453293		5.820	1.9186	0.360	9.687	0.385	15.5631
23	S70	0.400000			4.574	1.7515	0.382	12.041	0.396	16.2631
24	SD	0.300000		0.2949544	4.574	1.7515	0.382	12.041	0.396	16.2631
25	S30	0.300000			4.144	1.6799	0.393	13.157	0.400	16.5631
26	QD	0.251875		0.57541623	3.976	1.6501	0.403	13.644	0.402	16.8150
27	QD	0.251875		0.57541623	4.135	1.6808	0.413	13.157	0.405	17.0669
28	S30	0.300000			4.553	1.7535	0.424	12.041	0.409	17.3669
29	BEND	2.400000	0.17453293		9.894	2.5147	0.481	5.413	0.457	19.7669
30	S70	0.700000			12.083	2.7879	0.492	4.247	0.481	20.4669
31	SF	0.000000		-0.1821779	12.083	2.7879	0.492	4.247	0.481	20.4669
32	S30	0.300000			13.116	2.9050	0.495	3.853	0.492	20.7669
33	QF	0.251875		-0.55821116	13.546	2.9514	0.498	3.703	0.503	21.0188
34	QF	0.251875		-0.55821116	13.038	2.8937	0.501	3.853	0.514	21.2706
35	S340	0.700000			4.153	1.4154	0.578	12.041	0.597	24.6706
36	SD	0.000000		0.2949544	4.153	1.4154	0.578	12.041	0.597	24.6706
37	S30	0.300000			3.767	1.2850	0.590	13.157	0.601	24.9706
38	QD	0.251875		0.57541623	3.624	1.1983	0.601	13.644	0.604	25.2225
39	QD	0.251875		0.57541623	3.785	1.1556	0.612	13.157	0.607	25.4744
40	S30	0.300000			4.195	1.1300	0.624	12.041	0.611	25.7744
41	BEND	2.400000	0.17453293		9.644	1.1180	0.685	5.413	0.659	28.1744
42	S70	0.400000			11.923	1.1700	0.695	4.247	0.682	28.8744
43	SF	0.000000		-0.1821779	11.923	1.1700	0.695	4.247	0.682	28.8744
44	S30	0.300000			13.001	1.1934	0.699	3.853	0.694	29.1744
45	QF	0.251875		-0.55821116	13.477	1.1912	0.702	3.703	0.704	29.4263
46	QF	0.251875		-0.55821116	13.018	1.1470	0.705	3.853	0.715	29.6781
47	S30	0.300000			11.959	1.0697	0.709	4.247	0.727	29.9781
48	BEND	2.400000	0.17453293		5.405	0.6472	0.757	9.687	0.788	32.3781
49	S70	0.700000			4.204	0.5817	0.781	12.041	0.798	33.0781
50	SD	0.000000		0.2949544	4.204	0.5817	0.781	12.041	0.798	33.0781
51	S30	0.300000			3.798	0.5536	0.792	13.157	0.802	33.3781
52	QD	0.251875		0.57541623	3.642	0.5400	0.803	13.644	0.805	33.6300

* B'/Brho for quadrupoles and B"len/Brho for sextupoles. With eddy current sextupoles, SF=-0.03981742, SD=0.49051380

FIG. 1

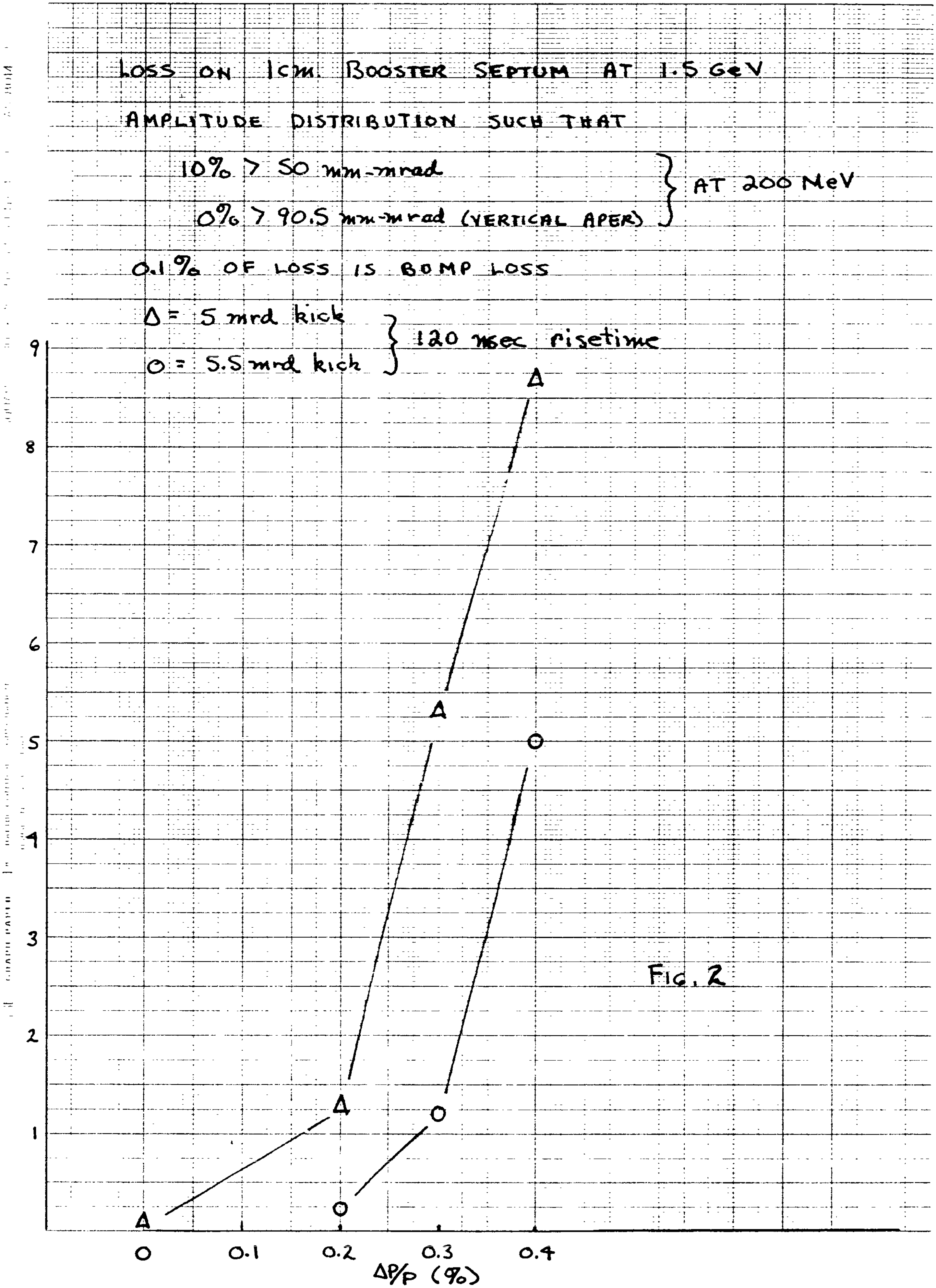
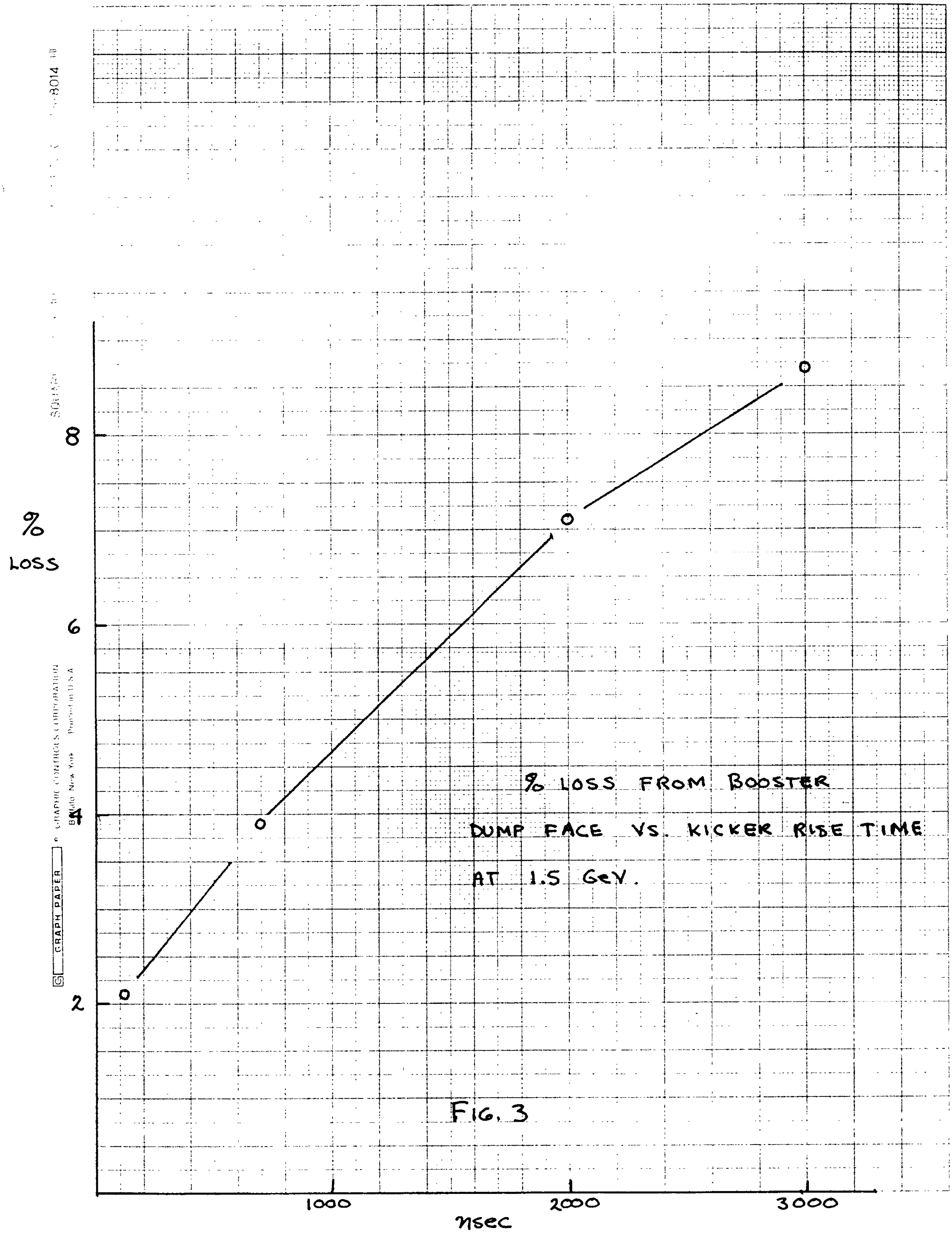

LOSS ON 1CM. BOOSTER SEPTUM AT 1.5 GeV
AMPLITUDE DISTRIBUTION SUCH THAT
10% > 50 mm-mrad
0% > 90.5 mm-mrad (VERTICAL APER)
AT 200 MeV
0.1% OF LOSS IS BUMP LOSS
Δ = 5 mrd kick
O = 5.5 mrd kick
120 nsec risetime
9
8
7
6
5
4
3
2
1
0
0.1
0.2
0.3
0.4
ΔP/P (%)

FIG. 2



% LOSS FROM BOOSTER DUMP FACE VS. KICKER RISE TIME AT 1.5 GeV.

FIG. 3