national accelerator laboratory

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REPETITION RATES OF BOOSTER AND MAIN RING

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A task team was formed to study the technical and economic features of various choices of the repetition rates of the booster and the main ring. Members of the team are:

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(A) Procedure

The invariant boundary conditions assumed are:

(1) The average current at 200 BeV should be 1.5 x 10^{13} p/sec.

(2) The main ring should be capable of a duty factor of 25% at 200 BeV.

(3) The injection and final energies of the booster are fixed at 200 MeV and 10 BeV respectively. (A supplemental study of the effects of reducing the final energy of the booster to 8 BeV will be presented in a separate report.)

(4) The design for the booster and MR magnets is assumed frozen, namely the ring radii and the magnet apertures are assumed fixed.

(5) The study is made taking each choice of rep-rates as the "design" and not as either a "preliminary phase" or an "improved phase" of operation, although the result of the study may indicate the advantage of operating the accelerator initially during a "preliminary operating phase" at reduced performance or the possibility of improving the performance by a later "improved mode" of operation. Following this philosophy we have taken injection of 13 booster pulses into the MR as the "design".

To proceed we chose a number of reference cases for study. For the booster rep-rate it is advantageous for operational stability to use sub-harmonics of 60 Hz, frequency of the ac main. We have therefore taken $\frac{60}{4}$ = 15 Hz, $\frac{60}{6}$ = 10 Hz and $\frac{60}{8}$ = 7.5 Hz as the values for study. In order to isolate the MR rep-rate from that of the booster we have specified for the MR the pulsing time (acceleration time plus recovery time) instead of the rep-rate and have more or less arbitrarily taken

the values 2.2 sec (present design) 3.2 sec and 4.2 sec for study. Thus, we have a matrix of 9 cases as shown in Table 1 where the pulse time and beam intensity requirements follow directly from the invariant boundary conditions.

(B) Performance Evaluation

(1) Linac Current

The required beam currents from the linac at four-turn injection into the booster are rather high for the lower rep-rate cases. These current requirements are calculated assuming no loss of beam in the transport system and during injection. In practice, the necessary currents may well be substantially higher than those given in Table 1. Although linacs of similar design have produced these high currents the output beam emittance and momentum spread are much larger than those assumed at the present for a lower "design" linac beam current of 75 mA. These poorer beam qualities will lead either to more loss during transport and injection or more stringent requirement on the booster components. It is possible to inject more than four turns thereby reducing the required linac current. This however means more careful control and tuning of the injection equipment. Nevertheless this is the simplest and most promising route to increasing the beam injected into the booster for given linac beam current and quality and should certainly be considered as a future improved mode of operation. In any case these considerations indicate a preference for the higher rep-rate cases.

(2) Transverse space charge effect

The incoherent transverse space charge limits corresponding to the latest magnet design parameters with closed orbit distortions and $\Delta\nu = 0.25$ are 7×10^{12} protons for the booster and 10^{14} protons for the MR. Although the "design" intensities for all the 9 cases are within these limits as shown in Table 2, for the low rep-rate cases the closeness of the required intensities to the space charge limits will most likely make their attainment require more time and critical tuning and will certainly impose a lower limitation on the ultimate capability in intensity.

In addition the coherent transverse oscillations induced by resistive wall effects, etc. having thresholds below the incoherence space charge limit will be more difficult to damp at higher required intensities.

These considerations lead to the desire for high rep-rates for both the booster and the MR.

(3) Longitudinal space charge effect

The most damaging effect is the mismatch in longitudinal phase space caused by space charge forces in crossing transition. This mismatch leads to oscillations in the shape of the bunches, which will then oscillate between a configuration having a larger extent and a larger momentum spread than the matched bunches that would exist in the absence of this effect. The effect is measured by the parameter η_o introduced by

Sorenssen, which is given in Table 2.

The blowup is particularly troublesome in the booster because there the margin between energy gain per turn and peak rf voltage is small. Therefore even a relatively small blowup-corresponding to $\eta_o \approx 3$ can lead to oscillations reaching to the limits of phase stability. Therefore higher rf voltages are necessary if η_o is large.

The values of η_o for the main ring are computed on the assumption that, by damping or otherwise, the blowup in the booster has been reduced to negligible proportions by the time the beam is transferred to the main ring. In the main ring there is a larger margin in the rf system, and blowup corresponding to $\eta_o \approx 5$ can probably be tolerated without beam loss.

Damping systems have been demonstrated to be effective, both in computations at NAL and in experiments at BNL, in reducing or eliminating the blowup. But during the damping process, which lasts for several phase oscillations, the higher rf voltages still have to be provided.

The triple-switch method of matching the beam in crossing transition proposed by CERN looks sound in principle but has yet to be demonstrated in practice. In any case the triple-switch matching procedure is also more difficult for larger values of η_o.

This consideration again strongly favors higher reprates for both the booster and the MR.

Other longitudinal space charge effects such as the resistive wall effect, although do not lead directly to deterioration of the beam quality, are all more serious at higher beam intensities.

To summarize, all space-charge or self-field effects which cause deterioration in beam qualities become more serious at low rep-rates because of the higher required intensity and the lower rate of acceleration. The degree of seriousness or the relative difficulties (measured in cost and manpower effort) in providing remedial measures is indicated by the parameters given in Table 2. These parameters therefore give a measure of the desirability for higher rep-rates.

(4) Phase Oscillation Frequency

The rep-rate of a synchrotron affects directly the phase oscillation frequency ν_s. Without space charge and if the rf cavities are not periodically arranged around the ring to eliminate the first harmonic the 1/4 integral resonances must be avoided, namely we must have $\nu_s < \frac{1}{4}$. There also is coupling between the phase and horizontal betatron oscillations; this coupling is strengthened by space charge forces. The effect of the coupling is to produce side bands at $\nu_x \pm n\nu_s$ (n = integer) on the horizontal oscillation thereby reducing the allowable range of horizontal tune shift due to space charge. For the magnitude of space charge force involved only the first side bands (n = ±1) have appreciable strength.

To avoid having the first side bands running onto integral or half integral resonances, and to maintain a reasonably large range for space charge shift of the horizontal tune, ν_s should not be larger than 0.1. This condition is satisfied through the acceleration cycle for both the MR and the booster in all the 9 cases considered. This consideration alone therefore does not lead to a clear-cut preference among these cases.

(5) Quality of beam spill

The longer flat-top of the MR required to provide the same duty factor of 25% at lower rep-rate means that the already exacting demands on the precision of regulation of all beam spill equipment such as the feed-back ripple suppressor, power supply for the tune-shifting quadrupoles, power supply for the sextupoles exciting the third integral resonance, power supply for the electrostatic septum and the septum magnets etc. will be more stringent in proportion to the flat-top duration. Without this additional effort and cost it is likely that the spill quality will deteriorate so that lengthening the magnet flat-top does not increase the effective spill length of the beam. The measure of relative difficulty in obtaining the necessary precision of regulation is indicated by the flat-top durations given in Table 1.

Thus, on all these accounts, one can state that for performance both "design" and "eventual capability" and in terms of the beam quality for doing experiments higher rep-rates for

both the booster and the MR are desirable.

(C) Cost Estimate

Under the invariant boundary conditions the major systems affected by the rep-rates are the rf system and the magnet power supply system. The differential costs for the 9 cases are given in Table 3.

(1) Main ring rf system

(a) For a fair comparison of systems with the same performance the estimates were made assuming the same cavity stored energy to beam power ratio for all cases.

(b) Reducing booster rep-rate increases the MR rf cost because of the increased intensity requirement.

(c) Lengthening the pulsing time of the MR reduces the rf cost because of the lower required voltage. However the reduction is partially off-set by the increase in beam intensity.

(d) For longer MR pulsing time the lower rf voltage required results in smaller bucket area. While the bucket area is adequate for ideal "design" conditions the blow-up due to longitudinal space charge effect at transition in the booster mentioned in (B) (2) may require larger bucket areas. In any case the reduction in bucket area means less reserve for dealing with eventualities and more exacting demands on the performance of all other component systems.

(e) For lengthened MR pulsing time the design of the MR rf system must be drastically revised, beginning with the basic cavity design. The same is true for reduced booster rep-rate, although the necessary design change is less drastic. The required manpower, time and cost for the design revision are not included in the cost estimate.

(2) Booster rf system

(a) The same cavity stored energy to beam power ratio is assumed for all cases.

(b) Lengthening the MR pulsing time increases the booster rf cost because of the increased intensity requirement.

(c) Reducing the booster rep-rate decreases the rf cost because of the lower required voltage. But the decrease is partially offset by the increase in beam intensity.

(d) Again it should be emphasized that the cost in additional design effort and time necessary for all but the presently adopted case of 15 Hz booster and 2.2 sec MR pulsing time has not been included in the estimates.

(3) Main ring power supply

(a) The pulsing time is divided into the acceleration (up) and the recovery (down) times in such a way as to allow proportionate amounts of time for transients and jitters on rectification and inversion.

(b) The booster rep-rate has only a slight influence on the cost of the MR power supply through the effect of the injection time on the rms power requirement.

(c) For the same duty factor the MR pulsing time has only a slight influence on the rms power requirement. Its influence on the cost of the power supply comes mainly from its effect on the peak power demand.

(d) Since the rms power consumption varies very little from case to case the present cooling system is adequate for all these cases.

(e) As was mentioned in (B) (3) increasing the flat-top leads to more stringent requirements on the regulation and feed-back control of the power supplies for the principal and auxiliary magnets of the main ring. This involves a sizable amount of development effort. The cost for this effort and time has not been included.

(f) It appears that the limitations imposed by pulsing the main ring directly from the power main do not cause any concern for any of these cases.

(4) Booster power supply

(a) The main ring pulsing time has no effect on the cost of the booster power supply.

(b) The booster rep-rate affects the sizing and, hence, cost of the power supply only through the rep-rate dependent eddy current loss in the magnet and the choke. For the rep-rates studied the eddy current loss is small. Therefore

the cost differentials are rather small.

(c) Since the total power loss is not too different for all these cases the present cooling system is adequate.

(d) A power supply designed for 15 Hz can be re-arranged to give $\frac{15}{2}$ = 7.5 Hz. But to get 10 Hz using the same components would be very difficult or impossible.

(5) Miscellaneous Items

In addition to the major systems mentioned above other smaller systems are affected either directly or indirectly by rep-rates. For example, the booster beam extraction system, the beam transport system between the booster and the MR, and the MR injection system need to operate only during injection into the MR. The same is true also for the booster rf system. The cooling for these systems could be sized according to its duty factor given by (booster injection time)/(booster cycle time). However the cost differentials for these items are so small that they are within the uncertainties in the cost estimates of the four major systems and are, therefore, left out.

(D) Conclusions and Recommendations

(1) The cost differentials among these cases are small compared to the total cost of the four major systems: being M$1.177 between the extreme cases which is only about 10% of the total of about M$12 [M$2.78 (MR rf) + M$4.33 (Booster rf) + M$4.10 (MR PS) + M$0.63 (Booster PS) = M$11.84] for the present

"design" case of 15 Hz booster and 2.2 sec MR pulsing time. This is because in the first place the specification of 25% duty factor makes the rms power requirement of the MR insensitive to rep-rate. Only the relatively small peak-power dependent portion of the power supply cost varies significantly with rep-rate. The same is true with the booster power supply.

In the second place, reductions of the rf costs at lower rep-rates due to lower required voltages are always partially compensated by increases due to higher required intensities.

(2) It is evident from Table 3 that the cost savings going from 15 Hz booster rep-rate to 10 Hz are much greater than those from 10 Hz to 7.5 Hz. This is exhibited more clearly in the plots of total cost versus booster rep-rate given in Fig. 1. Thus, starting from a low rep-rate booster the cost remains relatively constant as rep-rate increases until somewhere around 15 Hz when the cost rises steeply. Since performance considerations indicate that higher rep-rate is more desirable we should choose a "design" rep-rate as high as possible consistent with moderate cost. This criterion gives a value close to 15 Hz as the proper choice for the booster rep-rate.

(3) The plots of total cost versus MR pulsing time given in Fig. 2 do not exhibit the sharp rise and curvature as do the plots in Fig. 1. Within the range of MR pulsing time studied there is no clear break-point on either performance or

cost. This situation suggests the advisability for a two phase operation. We could choose the short pulsing time of 2.2 sec as the "design". For the "preliminary phase" we could operate the MR at a longer pulsing time, say, 4.2 sec, at a reduced performance. The operation at the longer MR pulsing time is obtained by simply omitting some of the power supply and rf modules designed for the shorter pulsing time of 2.2 sec, thereby avoiding the extensive design revision mentioned in (C) (1) (e). Although we cannot expect to obtain the "design" duty factor and beam intensity during the "preliminary phase" operation it will give us valuable operating experience in advance of the full "design" mode of operation and, perhaps, indicate more clearly the proper direction for future improvements.

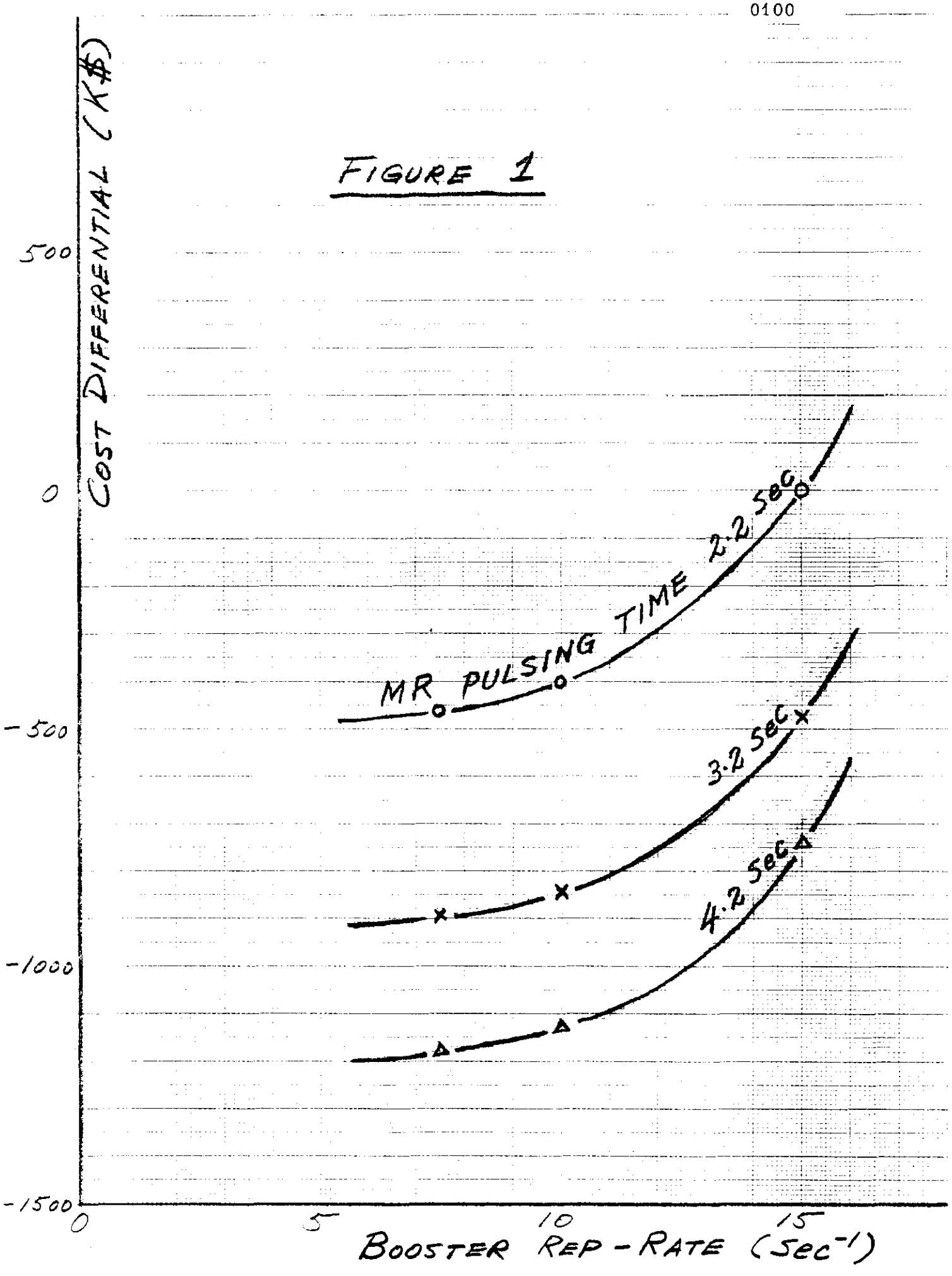
FIGURE 1
COST DIFFERENTIAL (K$)
500
0
-500
-1000
-1500
0
5
10
15
BOOSTER REP-RATE (Sec⁻¹)
MR PULSING TIME 2.2 sec
3.2 sec
4.2 sec

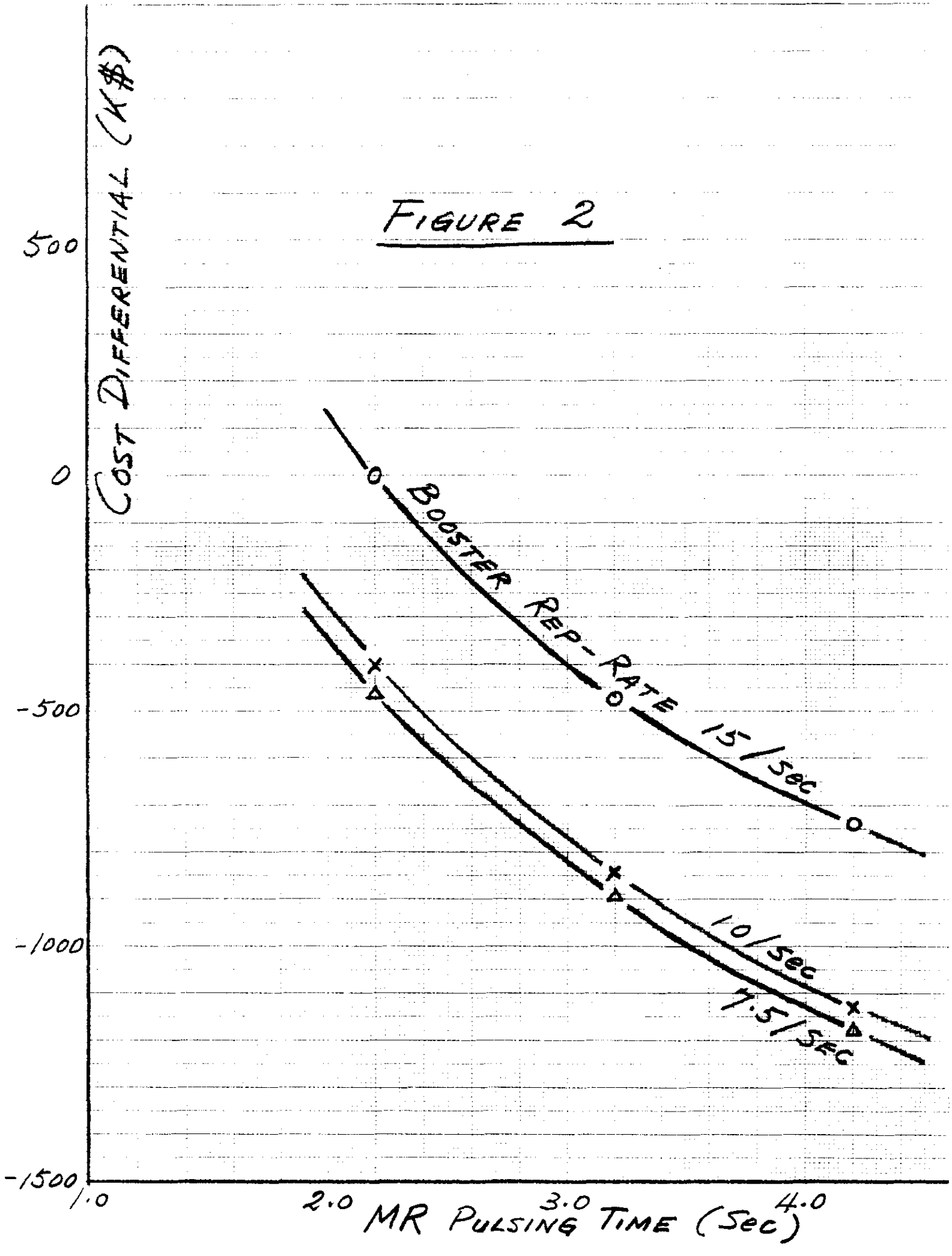
FIGURE 2
COST DIFFERENTIAL (K$)
500
0
-500
-1000
-1500
1.0
2.0
3.0
4.0
MR PULSING TIME (SEC)
BOOSTER REP-RATE
15/SEC
10/SEC
7.5/SEC

Table 1

Booster Rep-Rate (Injection time) / MR Pulsing Time	15 sec^{-1} (0.8 sec)	10 sec^{-1} (1.2 sec)	7.5 sec^{-1} (1.6 sec)
2.2 sec	T_O(MR)=3.0 sec T_F(MR)=4.0 sec I(MR)=4.5×10^{13}p/pulse I(B)=3.46×10^{12}p/pulse I(L)=50 mA	3.4 sec 4.53 sec 5.1×10^{13}p/pulse 3.92×10^{12}p/pulse 56 mA	3.8 sec 5.07 sec 5.7×10^{13}p/pulse 4.39×10^{12}p/pulse 63 mA
3.2 sec	T_O(MR)=4.0 sec T_F(MR)=5.33 sec I(MR)=6.0×10^{13}p/pulse I(B)=4.62×10^{12}p/pulse I(L)=66 mA	4.4 sec 5.87 sec 6.6×10^{13}p/pulse 5.08×10^{12}p/pulse 73 mA	4.8 sec 6.40 sec 7.2×10^{13}p/pulse 5.54×10^{12}p/pulse 79 mA
4.2 sec	T_O(MR)=5.0 sec T_F(MR)=6.67 sec I(MR)=7.5×10^{13}p/pulse I(B)=5.77×10^{12}p/pulse I(L)=83 mA	5.4 sec 7.20 sec 8.1×10^{13}p/pulse 6.23×10^{12}p/pulse 89 mA	5.8 sec 7.73 sec 8.7×10^{13}p/pulse 6.69×10^{12}p/pulse 96 mA

T_O(MR)=MR period w/o flat-top

T_F(MR)=MR period w flat-top

I(MR)=MR intensity
I(B)= Booster intensity
I(L)=Linac current

} Calculated assuming four-turn injection into Booster and 13 pulses into MR; and no loss during extraction, transport, and injection

Table 2

Booster Rep-Rate (Injection Time) / MR Pulsing Time	15 sec^{-1} (0.8 sec)	10 sec^{-1} (1.2 sec)	7.5 sec^{-1} (1.6 sec)
2.2 sec (1.6 sec up 0.6 sec down)	r(B)=0.49	0.56	0.63
	r(MR)=0.45	0.51	0.57
	η_o(B)=3.15	4.38	5.65
	η_o(MR)=5.96	6.77	7.57
3.2 sec (2.55 sec up 0.65 sec down)	r(B)=0.66	0.73	0.79
	r(MR)=0.60	0.66	0.72
	η_o(B)=4.21	5.67	7.14
	η_o(MR)-10.05	11.06	12.06
4.2 sec (3.51 sec up 0.69 sec down)	r(B)=0.82	0.89	0.96
	r(MR)=0.75	0.81	0.87
	η_o(B)=5.26	6.95	8.62
	η_o(MR)-14.74	15.91	17.10

$$r(B) = \frac{\text{Booster intensity}}{\text{Booster transverse space charge limit}} = \frac{\text{Booster intensity}}{7\times10^{12}\text{p/pulse}}$$

$$r(MR) = \frac{\text{MR intensity}}{\text{MR transverse space charge limit}} = \frac{\text{MR intensity}}{10^{14}\text{p/pulse}}$$

η_o(B) is calculated assuming that for 15 Hz the Booster RF voltage at injection is 100 KV and for other Booster rep-rates the RF voltage is adjusted to give the same bucket size at injection

η_o(MR) is calculated assuming that the MR and Booster RF bucket sizes are matched at beam transfer and no blowup in the booster.

Table 3

Booster Rep-Rate (Injection Time) / MR Pulsing Time	15 sec^{-1} (0.8 sec)	10 sec^{-1} (1.2 sec)	7.5 sec^{-1} (1.6 sec)
2.2 sec (1.6 sec up 0.6 sec down)	RF(MR)=K$ 0 RF(B) =K$ 0 PS(MR)=K$ 0 PS(B) =K$ 0 Total=K$ 0	K$ 294 K$-601 K$ -30 K$ -64 K$-401	K$ 888 K$-1200 K$ -59 K$ -91 K$-462
3.2 sec (2.55 sec up 0.65 sec down)	RF(MR)=K$-441 RF(B) =K$ 304 PS(MR)=K$-339 PS(B) =K$ 0 Total=K$-476	K$-117 K$-297 K$-364 K$ -64 K$-842	K$ 477 K$-896 K$-383 K$ -91 K$-893
4.2 sec (3.51 sec up 0.69 sec down)	RF(MR)=K$-735 RF(B) =K$ 520 PS(MR)=K$-524 PS(B) =K$ 0 Total=K$-739	K$-441 K$ -81 K$-542 K$ -64 K$-1128	K$ 153 K$-680 K$-561 K$ -91 K$-1179

RF(MR)=MR radiofrequency system cost differential

RF(B) =Booster radiofrequency system cost differential

PS(MR)=MR power supply cost differential

PS(B) =Booster power supply cost differential