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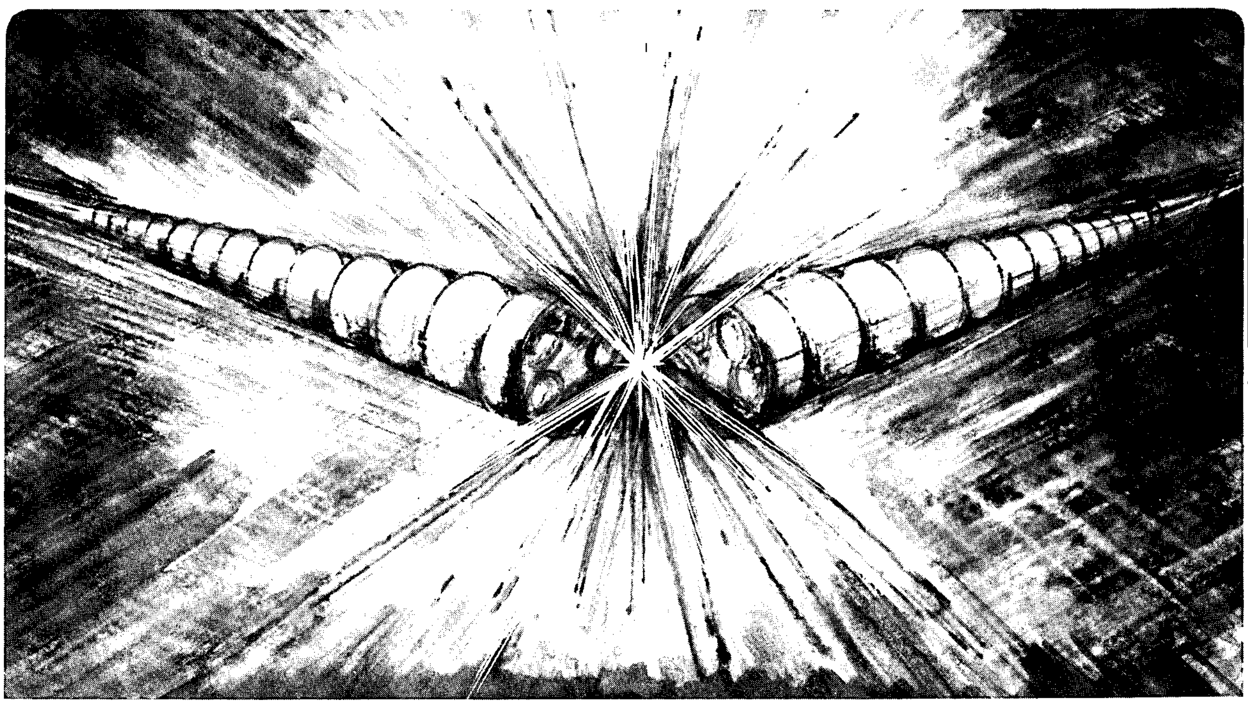
October 1992



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The Bevalac Long Flattop

I. Introduction

Until July of 1992, the maximum length of the Bevalac flattop[1] was 2 seconds, limiting the beam spill to 1.5 seconds[2]. The normal running condition was a 1.5 second flattop, with a 1.0 second beam spill. If we define the duty factor as the spill length (in time) divided by the synchrotron pulse length, that is, the percentage of time the Bevalac can deliver beam to experiments, the duty factor for the 1.5 second flattop ranged from 17% (at full field, i.e., 12575 G) to 25% (low field). The purpose of the Long Flattop Project was to increase the length of the flattop, thus increasing the duty factor of the machine, and its efficiency for experiments. This has been done, with resultant increase in the duty factor and experimental data rate. It is now possible to run with duty factor of about 80% for low fields, falling to about 60% at 10 kG, and 34% at full field. This report documents what was done, and its limitations.

It should be noted that increasing the length of the beam spill is only possible if the source can produce more beam per pulse than is usable by the experimenter. Experimenters running at full intensity with a short flattop (1.5 seconds) cannot benefit from a longer flattop.

The sections below describe the changes that have been made to Bevalac systems to make the long flattop possible, the limits put on the length of the flattop by existing hardware, and the procedure for tuning for the long flattop.

II. Limits on the Flattop Length

[1]The flattop is the time during which the main magnetic field of the synchrotron is held constant and the beam is extracted.

[2]The exception to this statement was a one-time-only half hour flattop done as a prelude to the building of the PEP accelerator.

The maximum flattop length which should be run at a given main magnetic field value depends on various limits set by software and hardware capabilities. These limits will now each be explained, after which we will describe the importance of these limits for different Bevalac operating regimes. Practical methods for deciding on a flattop length within these limits will be discussed in Section III.

The maximum possible flattop length is set by the following 6 limits:

1. 10 second control system software limit;
2. RMS power limit of IPB and EPB magnets[3];
3. RMS input power limit of motor generators;
4. Length of the pulse at a given machine rep rate;
5. Synchronization of the 2 MG's;
6. Main magnet heating.

The first of these limits is arbitrary, and simply means that the BMAG program will not allow any flattop longer than 10 seconds.[4] Since about 0.5 seconds is needed at the beginning of the flattop to set the extraction conditions and let transients die out, the beam spill is limited to 9.5 seconds.[5]

If the IPB (Internal Particle Beam) and EPB (External Particle Beam) magnets are run at too high a power level, they will overheat. Since the heating for these magnets (with the exception of XM1 - see Appendix A) occurs over a time period much longer than one synchrotron pulse, it is the rms power that is important, rather than peak power. All IPB and EPB magnets except those in the Biomed beamlines were checked to make sure that they would be within

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[3]"IPB" refers to "Internal Particle Beam", i.e., magnets within the synchrotron which are used to spill the beam, while "EPB" means "External Particle Beam", and refers to beamline magnets.

[4]The 10 second limit is arbitrary, and may be lengthened as much as desired (without much difficulty) by a control system programmer. Particularly at low fields, this might increase the available duty factor by 10 or 20% above that given by the present limit before one of the other limits pertains. However it should be noted that no one has tested magnets, etc., for flattops longer than 10 seconds, and there may be problems that are not apparent without careful review of the Bevalac systems. It is hoped that this paper might be a guide for anyone undertaking such an upgrade.

[5]It is assumed in the rest of this paper that the spill length is the flattop length minus 0.5 seconds. This is the case in daily operations at present.

normal operating limits for a flattop of 10 seconds at 10 kG main field, and rep rate of 4.6 pulses per minute. These were the original specifications for the project. [The magnet tests are described in more detail in Appendix A.] Therefore the significance of limit #2 is that the flattop length should not exceed that length for which the rms currents for these magnets are their rms currents at 10 kG, 4.6 ppm, for a 10 s flattop.

If we assume that the magnets follow the current profile shown in Fig. 1 [6], then the rms current for a given main field, B, is

$$I_{rms} = I_0 F, \tag{1}$$

where F, the form factor, is

$$F = \sqrt{\frac{T_1 + T_2 + 3T_3}{3T}} . \tag{2}$$

Here I_0 = flattop current for the magnet, and for any given operating profile T_1 = time for main magnet to ramp to field, T_2 = time for main magnet to ramp down to zero field, T_3 = flattop length, and T = the pulse length. Using eqs. (1) and (2) and the fact that saturation is not important in the IPB and EPB magnets (so that their currents are proportional to their magnetic fields, which are in turn proportional to the value of the main field) we can express the power limit as the following limit on the flattop length:

$$\frac{T_3}{T} \leq \frac{(0.92 \times 10^4)^2}{B^2} - \frac{T_1 + T_2}{3T} , \tag{3}$$

where B is expressed in Gauss. The constant 0.92 is the form factor for a 10 s flattop at 4.6 pulses per minute, using T_1 and T_2 for 10 kG. The limit shown in Eq. (3) has been put into the control system.

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[6] As described in Appendix A, except when the TOAD feature is turned on, the magnets are turned on at Magon, and some may come to field before the main magnet. In this case they are at field longer than would be calculated using eq. (1) with the current profile described. This can mean that the rms power is about 7% greater than what is calculated here. Since no Bevalac magnets are within 7% of their power limit at 10 kG for the long flattop, we feel that this is not a problem.

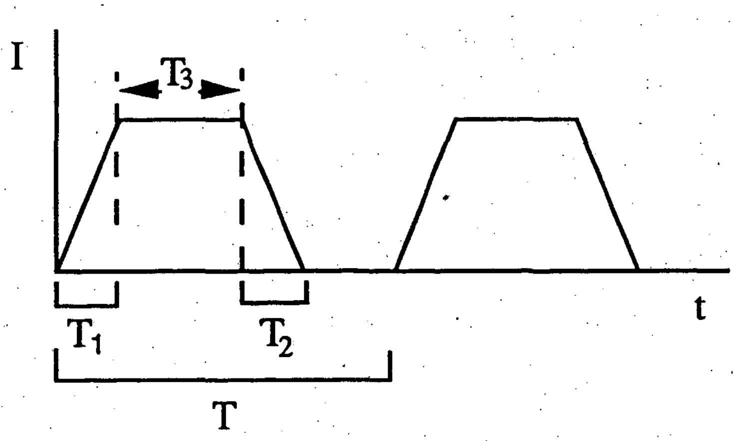

Fig. 1

The third limit is given by the specifications for the motor-generator set. The input power to the motors should not exceed 3.3 MVA per motor, rms. A normal value for the power factor is 0.8, giving a limit of 2.64 MW per motor. Of this, there are 0.52 MW per machine of fixed losses due to friction and windage. The voltage drop across the 4 ignitrons contributes a small amount to the losses. From data taken in 1949, this was estimated to be

$$P_{rms}^{ignitrons} \approx 50\ I_{avg} \tag{4}$$

per MG, where I_{avg} is the time-averaged main magnet current for the pulse. The I^2R losses in the motor and generator are also small. Again, scaling from 1949 data, we have

$$P_{rms}^{resist} \approx 0.0951\ I_{rms}^{2} \tag{5}$$

for 1 machine operation. Here, as above, I_{rms} is the rms current in the main magnet. Finally, we have the resistive losses in the main magnet, which has a resistance of about 0.26 Ω. This gives:

$$P_{rms}^{magnet} = 0.26\ I_{rms}^{2}\ . \tag{6}$$

So limit #3 for 2 MG operation is:

$$1.04\ \text{MW} + 100\ I_{avg} + 0.0476\ I^2_{rms} + 0.26\ I^2_{rms}$$

$$\leq 5.28\ \text{MW}. \qquad (7)$$

For 1 MG the limit would be

$$0.52\ \text{MW} + 50\ I_{avg} + 0.0951\ I^2_{rms} + 0.26\ I^2_{rms}$$

$$\leq 2.64\ \text{MW}. \qquad (8)$$

Our limited experience at this time shows equations (7) and (8) to be accurate to approximately 5%. For example, for a 9.5 second flattop at 7650 G with one MG running, eqs. (4) - (6) give 2.3 MW of input power, while MG power meters (accuracy unknown) show 2.4 MW at the beginning of flattop, rising to 2.5 at the end. At full field, the equations accurately predicted that the MG's could safely run about a 4 second flattop.

Limit # 4 is simply that sum of the flattop length, the time for the magnet to ramp up and down, and 540 ms (for the control system computers to send out timing pulses), must be less than the pulse length.

Limit #5 was found empirically. At high field (2 MG's), the two motor generator sets must be synchronized in order to balance the load. If the flattop is too long, they will not stay synchronized. It is thought that this is due to the fact that the Kramer system[7] cannot keep up the motor speed during the long flattop. As the motors slow down, they slow at different rates, thus producing a phase difference between the machines.

Finally, the flattop length is limited by the heating of the main magnet (limit #5). If the weather is hot, the main magnet coils will overheat at very high fields even with a 1.5 second flattop. Obviously then the flattop length must be cut back.

Given these limits, what length flattop is possible? The answer depends on the main magnetic field value and the synchrotron repetition rate.

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[7]The Kramer system consists of two induction motor-generators whose power is used to supplement the public power line when flywheel speed drops during peak power use.

According to the above limits, for 1 MG operation (B ≤ 7650 G), the currents in magnets are low enough that at any given repetition rate (i.e., at any given pulse length), the Bevalac is capable of running the longest flattop (≤ 10 seconds) that will fit within the pulse length. In other words, only limits 1 and 4 apply. Table 1 shows flattop length vs. rep rate for 7650 G, along with the duty factor this implies. The duty factor vs. rep rate is graphed in Figure 1, where the influence of limits 1 and 4 is clear.

It is hard at this time, with the amount of experience available, to give the maximum flattop limits for fields above 7650 G, since the restrictions placed by MG synchronization and main magnet heating cannot be calculated. An exception to this statement is that at high repetition rates (small pulse lengths and shorter flattops) the flattop is still limited by the pulse length-- power, heating, and synchronization limits do not apply. The IPB and EPB magnet power limits restrict the flattop length at low rep rates for fields above 10 kG. The MG power limit only restricts the flattop length at full field. Based on limited experience, at this time it seems that for fields below full field and above about 8 kG (?)(all we know is that the limit is between 7650 and 10000 G), the pertinent limitation of the flattop length is MG synchronization. At 10 kG, MG synchronization limits the flattop length to < 7 seconds. At "high fields" (≥ about 7 kG) main magnet heating due to the ambient temperature can limit the flattop further on warm days. And at full field, the flattop length is

Repetition Rate (pulses per minute)	Max. Flattop (seconds)	Duty Factor
4	10.0	0.63
4.286	10.0	0.68
4.615	9.8	0.72
5	8.8	0.69
5.455	7.8	0.66
6	6.8	0.63
7.5	4.8	0.54
8.571	3.8	0.47
10	2.8	0.38
12	1.8	0.26
15	0.8	0.08

Table 1 Maximum Flattop Length vs. Rep Rate at 7650 G

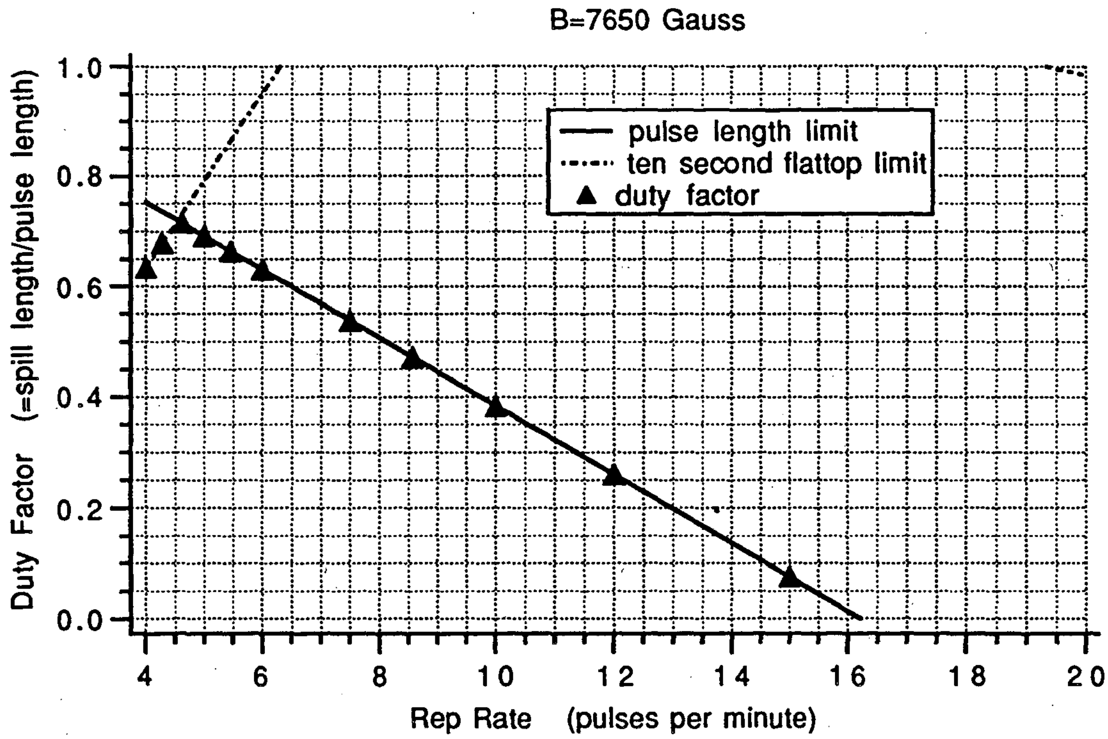

Figure 1

Repetition Rate (pulses per minute)	Max. Flattop (seconds)	Duty Factor
4	6.1	0.37
4.286	5.6	0.36
4.615	5.1	0.35
5	4.6	0.34
5.455	4.1	0.33
6	3.6	0.31
7.5	2.6	0.27
8.571	2.1	0.23
10	1.6	0.19
12	0.6	0.02

Table 2 Maximum Flattop Length vs. Rep Rate at 12575 G
Note: MG synchronization and main magnet heating neglected.

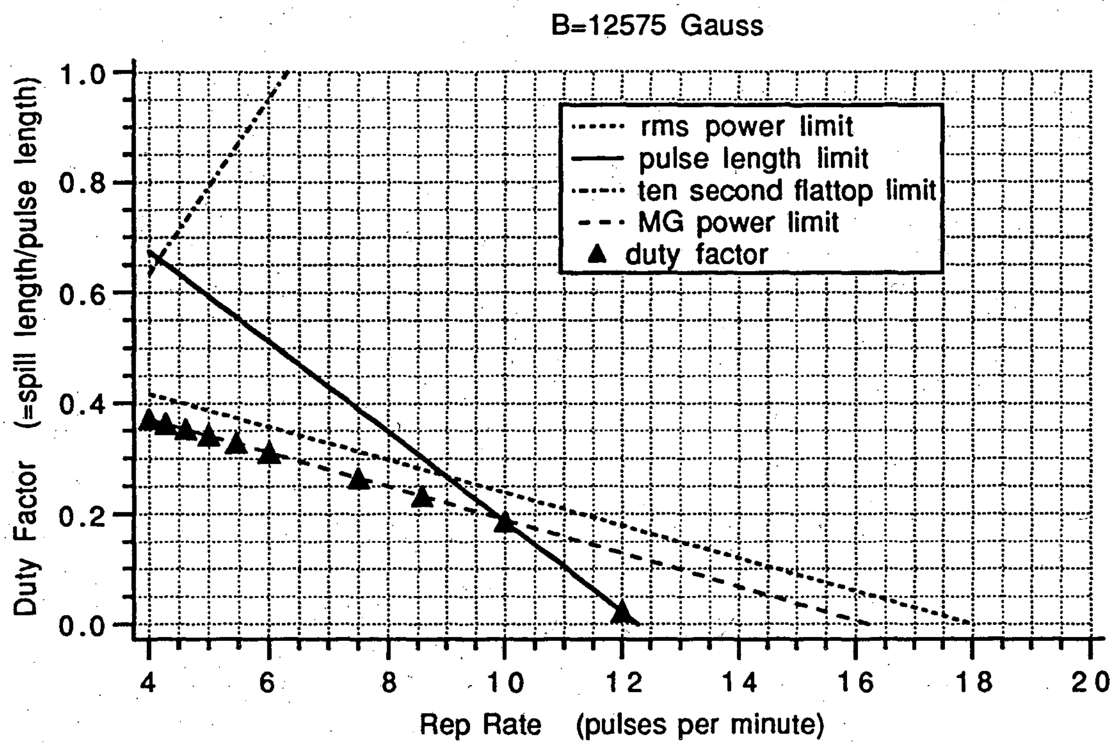

Figure 2

the MG power limit and by main magnet heating on hot days. A flattop length of 4 seconds at 5 pulses per minute has been run successfully at full field (12575 G) with cool ambient temperatures. Table 2 and Figure 2 show the maximum flattop length as a function of rep rate at 12575 G. This figure is meant to show the influence of the above limits at full field. It is to be remembered, however, that the limits given by MG synchronization and main magnet heating are not included in the graph and table, and may limit the flattop length, especially at low rep rates.

If we neglect main magnet heating and problems with MG synchronization (which perhaps could be corrected), as in Figs. 1 and 2 we can use the other limits to calculate duty factor vs. repetition rate for any field. This gives a maximum duty factor available for a given field, and the corresponding spill length and rep rate for which that maximum duty factor occur. These are shown in Figures 3, 4, and 5. Because the rep rates are quantized, the spill length graph is not monotonic. As magnetic field increases, the time to ramp the main magnet (up and down) increases, and the spill length possible decreases. When the spill length has fallen enough, it is

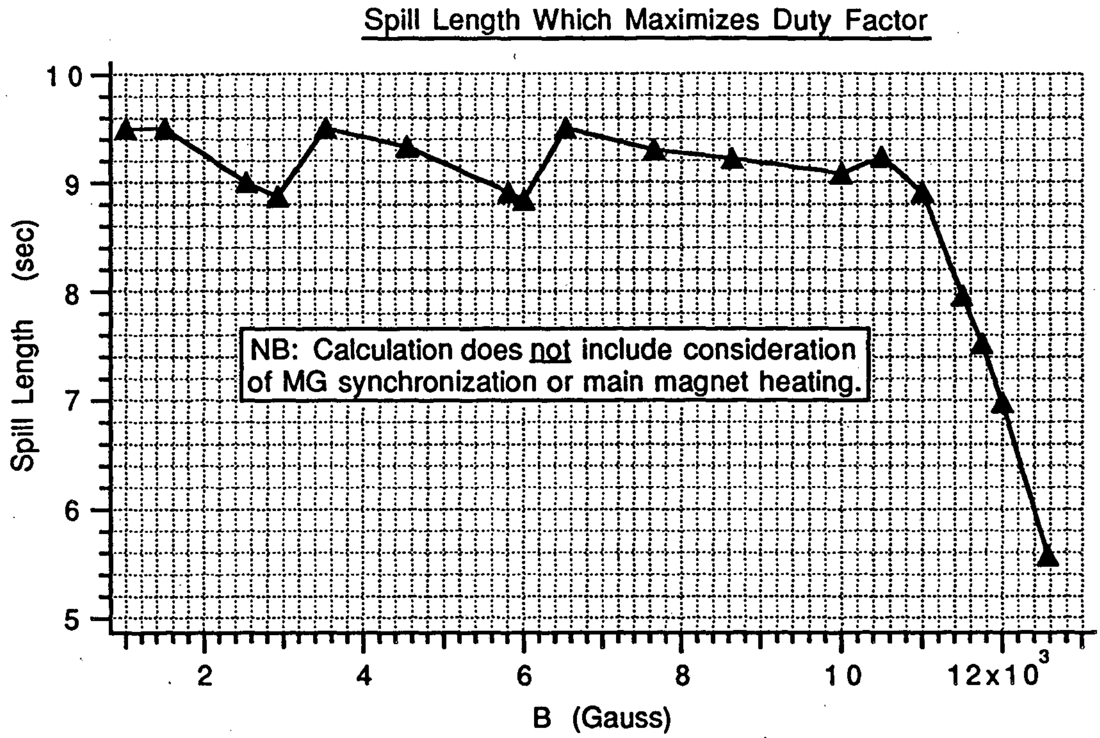

Figure 3

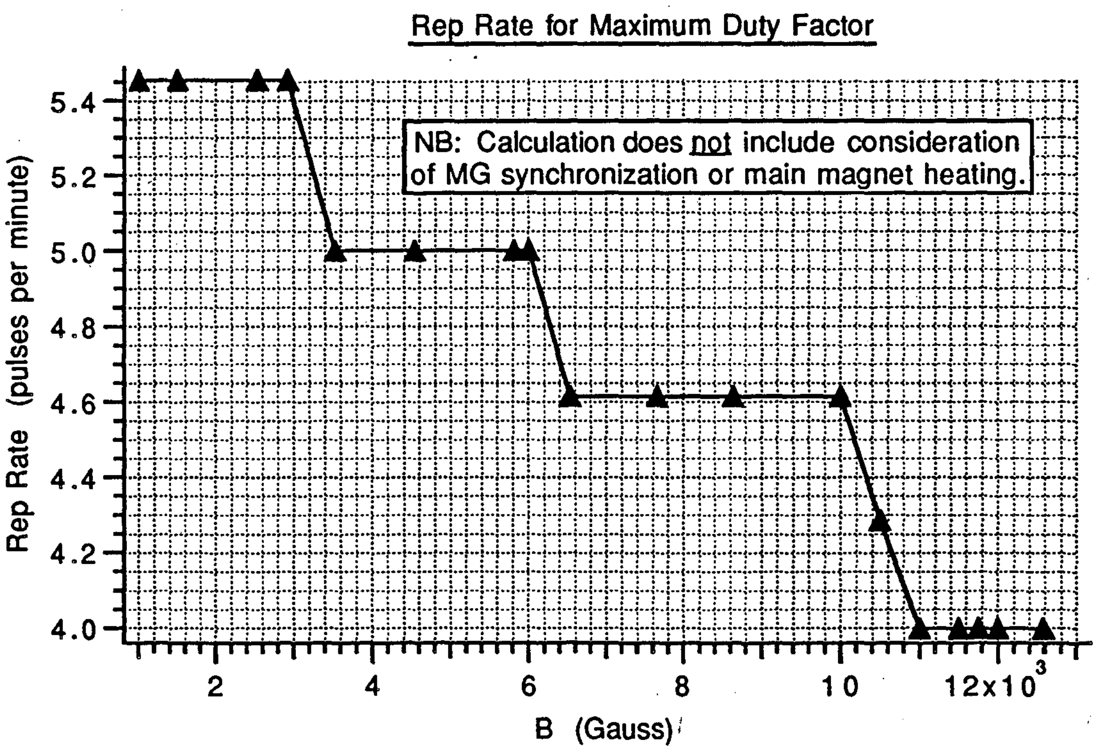

Figure 4

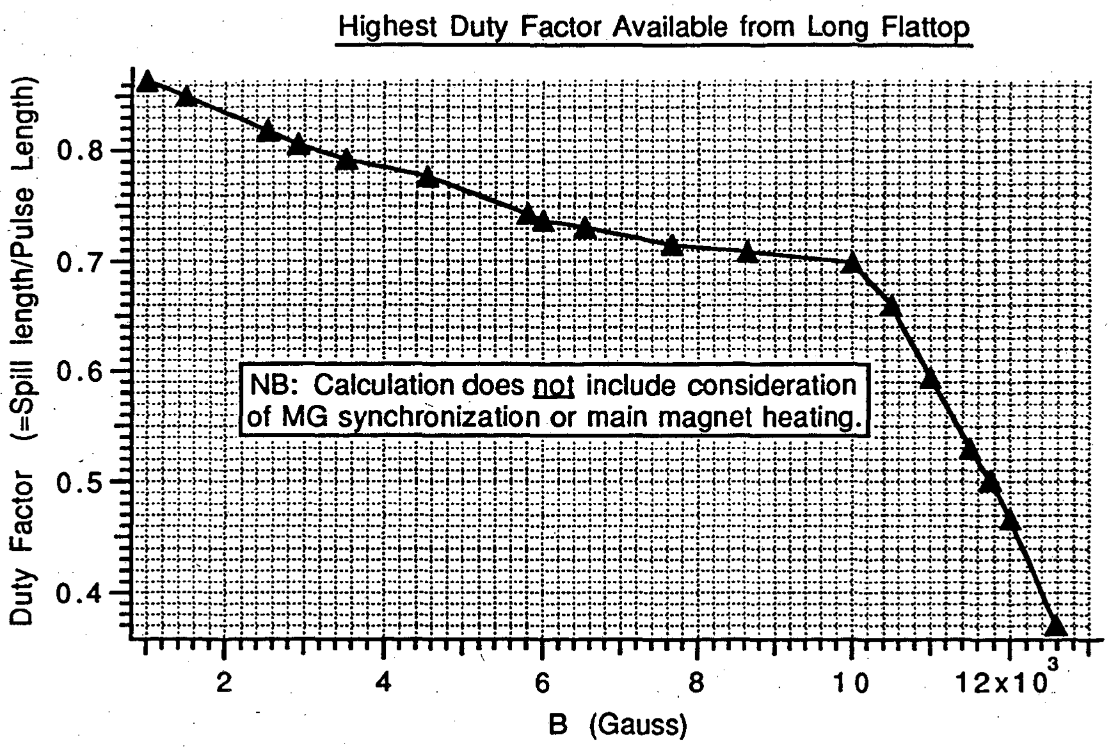

Figure 5

advantageous to decrease the rep rate and lengthen the spill in order to increase the duty factor. Figure 5 shows that the maximum duty factor decreases with increasing magnetic field. For fields up to about 10 kG this is due to more and more of the pulse being occupied with ramping the magnet, thus allowing less time for spilling beam. Above 10 kG, as mentioned above, power limits on the EPB and IPB magnets set in, followed by the power limit on the MG's near full field. These power limits cause the allowable duty factor to drop off quickly with increasing magnetic field above 10 kG.

III. <u>Setup and Tuning for the Long Flattop</u>

A. Selecting the rep rate and flattop length

The choice of flattop length for a given experiment may be made by optimizing the duty factor, subject to the Bevalac limits described above. However, the experimenters' equipment-- in particular, their data acquisition system-- may require a given flattop length or dead time between pulses. Or, given the particle rate requested by the experimenter, the available intensity may provide the lowest limit on the flattop length. In any of these cases, graphs and tables like those shown in Tables 1 and 2 and Figures 1 and 2 can be used as a guide to determine the optimum flattop length. These graphs are made by the macros "Optim" and "OneMG", which run at this time on a Macintosh PC under the program "Igor". At present Christine Celata and Marsh Tekawa have copies of this program. Results for a selection of magnetic fields are given in Appendix B.

It has proved useful in these first few months of long flattop operation to present the experimenters with a table and graph for each main field value at which they run, and let them choose the rep rate - duty factor combination that is best for them. It is of course true that at any of the rep rates shown, the flattop can be shortened from the values given in the table. These are maxima. A shorter flattop may better suit the experimenters' apparatus, though it will decrease their duty factor.

It must be made clear, however, that for 2 MG operation (B > 7650 G) MG synchronization and main magnet heating may decrease the flattop length available from that shown in the table (see Section II). We have some experience with this, but not much-- we know that at 10 kG we cannot run more than a 7 second flattop, and that at 12575 G, 4 seconds is possible, ambient temperature permitting. If an experiment is run in the field range where these limits might pertain, one must ask the MG operators to experiment with the MG's to find the maximum flattop length where the synchronization is good and the magnet temperature within normal limits. Next, choose the repetition rate which will maximize the duty factor at this flattop length (the duty factor vs. rep rate table will be helpful), and again check the synchronization and magnet temperature at the new rep rate. If either show problems, lower the rep rate or flattop length-- whichever decreases the duty factor the least.

If the flattop length is set, it is important to use the highest rep rate which will permit this flattop, subject to experimenters' restrictions. This will maximize the duty factor. It is easy to lose the gains we have made in duty factor by dropping the rep rate.

It is not always easy to change the rep rate, however. If the rep rate or flattop length are changed, the intensity of the circulating beam changes. This is probably due to the change in residual main field, and is especially devastating for protons, where injection is quite delicate. There is therefore often a tradeoff between the time needed to re-tune at a different rep rate, and the gain in data rate to be had from optimizing duty factor. For heavy ions, especially in the case where the experiment uses very low intensity so that changes in the circulating beam intensity can be offset with attenuators, re-tuning is probably the best course to take.

B. Lengthening the Flattop and Spill

Part IIIA describes how to choose the pulse rep rate and flattop length which will optimize experimental conditions. As mentioned there, when lengthening the flattop during 2 MG operation, it is important to make sure that the MG's can synchronize. Once the flattop has been stretched, the MG feedback loops must be properly tuned for the new length. The di/dt chassis, which controls low frequency ripple of the alternators must be retuned (by MG operators) to give the least variation of the magnetic field for the new flattop length. As with any increase in time-averaged power, warm-up time is required for the MG's to lengthen the flattop.

To lengthen the spill, the following must be changed:

1. Gates for plunged magnets (Mice)
2. P1, S1 gates (on perturbation unit display)
3. Spill gate (on Spiller display)
4. Extraction pole face windings Flattop Zone 1 length
5. Circulating intensity (to keep extraction efficiency reasonable).

Important Note: There is danger of overheating the pole-face windings if they are run for a 10 second flattop at currents above 50 A. At this time the only protection for them is dash-pot time-overcurrent protection. The adequacy of this protection is currently under review by Roger Dwinell and Blair Jarrett. It is also planned to implement a power limit in the control system software, but that is not yet underway. At the present time, all flattops longer than 2 seconds should use extraction pole-face winding currents that are ≤ 50 A.

Please note that checks on the power limits for the IPB magnets did not include P2, as it was decided that P2 was unnecessary. Using P2 for long flattops may or may not result in over-temperature trips.

The TOAD (turn on after delay) feature in the control system should be used for long flattops for fields at or above 10 kG. This feature lets the control system turn on each EBP magnet at the correct time for it to reach its current and stabilize before the beam spills. The alternative, which runs more power through the magnets, is to turn on all of the magnets at Mag-on, regardless of how long it takes them to come to field.

C. Diagnostics

The rf cannot be left on throughout the long flattop at its maximum value without damaging the rf system, so the control system will not allow this. Therefore, if one desires to leave the rf on in order to use the BIE (or in order to have an rf-on spill for any reason), one must use the control system feature which decreases the rf during flattop. This is found on the BevRF display.

At this time, the wire chambers will not integrate over a 9.5 second spill. New hardware and software is being developed, and the wire chambers should read for the full length of the flattop and do multiple reads through the long flattop by Nov. 1.

D. Spill Structure

Spill structure is extremely important for long flattop tuning. Tuning to optimize spill structure will be discussed in Section IV.

IV. Spill Structure

A. The Problem

Since the spill efficiency for a long flattop is the same as for a short flattop, the amount of particles per unit time spilled is up to 9.5 times less than for the short flattop. (Spill efficiency is defined as the number of particles spilled divided by the number circulating.) This means that with the long flattop we are trying to control the beam with stricter tolerances, though the difficulty in doing this, the magnetic field ripple, may remain the same as with the short flattop. For this reason, it is especially important when using the long flattop to watch the spill structure and do anything possible to improve it. Different experiments are bothered by different frequencies in the spill, but in general most are looking for as little variation in the magnitude of the spill as possible. In the rest of this section, spill structure and methods for improving it will be discussed.

B. Causes and Nature of Spill Structure

There are two main causes of spill structure: magnetic field ripple, and oscillation of the spiller chassis. Most magnetic field ripple comes from MG rectifier ripple, and is at multiples of the fundamental MG frequency. It is important at frequencies ≤ about 2 kHz. However there are important oscillations at low frequency--around 5 Hz, and near the MG shaft resonance frequency of 21 Hz.

The spiller chassis oscillation is well known, and is due to a delay of ~100 μs in the feedback loop (see Appendix C). It turns the spill on and off at about 2.5 kHz. Recently an oscillator has been installed in the spiller chassis that causes the spiller magnet, S1, to oscillate for non-experimenter feedback spills at about 10 kHz. This oscillator decreases the amplitude of the spiller oscillations by spilling the same amount of beam at 10 kHz that was being extracted at 2.5 kHz. Its operation and function is explained in Appendix C.

C. Monitoring Spill Structure

Given the frequencies involved, it is important to monitor the spill on a time scale that is shorter than that which has been generally used in the past. For this purpose a storage oscilloscope has been installed in the Main Control Room in rack C10. For non-experimenter feedback spills, one should watch the "spill" signal (from the "spill" spigot on the spiller chassis) on a time scale around 0.2 - 1.0 ms per division in order to see the effect of adjustments in extraction on the spill structure. [If one is looking for higher frequency structure, it is important to note that the spiller current-to-voltage converter response is down to 50% of its DC value at 20 kHz.] The goal is to decrease the height of the spill spikes while keeping the particle rate constant.

For experimenter feedback spills, the signal from the spiller chassis "spill" spigot is a logic signal whose width can be large enough to mask behavior at frequencies of interest. It is best to look at the output of a PM tube signal at the experimental cave. The 'scope time scale should in general be the same as for the higher intensity analog-feedback spills, though in this case it may be important to the experimenters that structure be optimized on some faster time scale.

The ("Signology") Tektronix spectrum analyzer is also an excellent tool for observing spill ripple.

D. Improving the Spill by Decreasing Magnetic Field Ripple

Since much spill time structure is caused by magnetic field ripple, it is important that the systems that remove that ripple be tuned properly.

As mentioned in Section III B, MG operators should be careful to re-tune the di/dt chassis to minimize low frequency field changes whenever the flattop length is changed.

The ripple reduction system should be retuned whenever the magnetic field is changed substantially. If the ripple reduction is not tuned well, the spectrum analyzer ("Signology") shows a bump in the spill spectrum at about 10-17 kHz which disappears if the rip red is turned off. In extreme cases, there is a huge spike in the spectrum, showing oscillation in the rip red.

Finally, if spill structure is crucial to an experiment, changes in the main magnet filter frequencies can be considered. The filters have narrow bandwidth-- especially the filters at 355 Hz-- and the MG rectifier frequencies depend on magnetic field. Therefore at some values of the main magnetic field the ripple frequency is not at the center of the filter. Thus spill structure can be improved, albeit with considerable effort, by changing the central frequency of the filters.

E. The Effect of Extraction Tuning on Spill Structure

In Part A of this section, we discussed how spilling a very low percentage of the beam per unit time can decrease spill structure quality. It is important to note that this will happen for any flattop length if the extraction efficiency gets too low. For both experimenter feedback and regular analog feedback spills, the extraction efficiency should be kept in a normal range (that is, as high as is possible without too many short spills) in order to get the optimal spill structure. This is doubly important for long flattops. For experimenter feedback spills, experimenters can change the amount of beam extracted without the knowledge of a Bevalac operator. They should be advised to inform the operator of changes in extracted particle rate so that the circulating beam intensity can be changed to keep the efficiency reasonable.

The beam extraction radius, extraction pole-face windings, and the current setting for the P1 magnet have been observed to affect the spill structure in various ways. Large spikes in the spill have been removed by moving the radius (inboard), while having the radius too far in has caused the variation in the spill amplitude to increase. It is important when tuning extraction to vary the extraction radius while monitoring spill structure, using the radius to optimize spill structure. This is also discussed in Appendix C in some detail as it applies to adjusting the 10 kHz oscillator in the spiller.

It is not always possible for the feedback system to control P1 spill-- i.e., spill that is present when P1 is on and S1 is not. If there are large spikes in the spill, especially at low frequency (around 5 Hz) where our largest magnet ripple resides, check for P1 spill by turning off S1. P1 spill should be minimized as well as possible.

F. The Spiller Feedback System and Spill Structure

The spiller feedback system has a few controls which can affect spill structure. One is the 10 kHz oscillator mentioned above. This oscillator does not work during experimenter feedback spills. If the frequency and amplitude of the oscillator are adjusted properly, the spill turns on and off at about 10 kHz. At this time, we have limited experience with the oscillator, but believe that at least the frequency should not vary with changes in field or accelerator tune. But if non-experimenter feedback spills are not extracted at 10 kHz, adjust the oscillator.[8] Appendix C describes this process.

The spiller loop gain also changes spill time structure. The higher the loop gain, of course, the better the system can control magnetic field ripple. So this adjustment can be used to effectively remove low frequency ripple from the spill. However, increasing the gain of the system leads it to overshoot more when it reacts to changes in the spill intensity. With the 10 kHz oscillator working, this is not likely to significantly affect the spill, since it is the oscillator which is turning the spill off (open loop) faster than the feedback system can react. Thus with this system on it may be possible to increase the loop gain for non-experimenter feedback spills above what has been customary, removing time structure due to magnet ripple. Again, the best course is to increase the loop gain while watching the spill on the oscilloscope on a time scale of about

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[8]If the frequency is close, but not quite what it should be, there may be "beats" in the spill-- amplitude modulation on a somewhat longer time scale than 10 kHz. Magnetic field ripple, however, also gives variation on slower time scales at the frequencies described in Section IV b. The oscillator is tuned to the frequency of the delay time (see Section IV B), which has been observed not to vary significantly, so it is hoped that adjustment is not necessary.

0.2 - 1.0 ms/div. For experimenter feedback spills Mark Nyman has suggested that the loop gain be kept low, but above 100.

It is important that the spiller reference, i.e., the "rate" should be kept in the normal range (around 3) as shown by the gauge on the upper right of the spiller chassis. If the reference is too low, then the incoming signal from the spill is kept low also by the system, and will be more affected by noise.

Finally, it is good to check noise on the signals to the spiller from the F1 PM tubes and BFDs periodically-- at least every 4 months-- by observing the signal with the main magnet pulsing and the EOS cup in (no beam). The noise should be a few millivolts for low PM tube voltage, rising when the voltage gets to about 1700 V. More noise can be caused by ground loops or by failure to twist the high voltage and signal cables from each tube together, creating a bdot loop. The spiller assumes the noise is spill structure and "corrects" for noise on the cable, thus putting the noise into the spill. Note that the spiller current to voltage converter, as mentioned above, filters out signals at hundreds of kilohertz and above, so noise at these frequencies is only important to those wishing to look at the PM tube signals directly.

G. RF-on Spills

One final way to change the spill structure a great deal is to leave the rf on during the spill. This not only puts the rf structure into the beam, but it also counteracts the ability of the magnetic field ripple to move the beam radius, thus removing much of the effect of magnetic field ripple on the spill. When the rf is on, its frequency is changed by the control system to compensate for changes in the magnetic field (as read by the bdot loop) and keep the radius constant. As mentioned in Section III C, for a long flattop the rf amplitude must be turned down during the flattop. It is not known how this affects the radial feedback.

While radial feedback via the rf removes low frequency spill structure, experiments may be sensitive to rf structure in the beam.

V. Control System Changes

The following modifications to the Bevalac control system were made in order to implement the long flattop:

• BMAG, the program that controls the fundamental Bevatron cycle, was altered to allow long flattops. Several details were involved. First, a new set of cycle lengths were selected and set into both the field-and-time scalar hardware and the software; the operator input was changed from "rep-rate" in pulse/minute to its reciprocal, seconds/pulse, the latter being a simpler number. Second, since the scalar hardware cannot scale a single segment beyond about 2 seconds, additional segment boundaries were created to break up the long time segment. Third, the operator interface was changed to show additional information during the long flattop.
A power limit for the IPB and EPB magnets was incorporated into the profile generation routine (see Section II).

• The East and South mouse timing was disconnected from the old hardware timing circuits and connected to digital outputs from the computer. Algorithms and operator interfaces were implemented for both "look and adjust" and save/restore with other parameters.

• Additional circuitry from the Bevatron RF was connected to the computer to allow the operators to select between RF-Off and Flattop-Off for the Saturable Reactor Off time, and for setting the level of the low-level RF signal (see Section III C).

• Operator interfaces that control the spill gating were extended to allow long flattop times: main spill, pole-face winding extraction gate/delay, EPB perturbation unit gate/delay. N.B.: it was not possible to overcome limitations in the 8086 interface firmware, so the Wire Chamber software DOES NOT accommodate long flattop.

VI. Changes Made to the Bevalac to Implement the Long Flattop

Changes that have been made to the Bevalac systems to implement the long flattop are mentioned throughout the text and appendices of this report. A list of the changes can be found in Appendix D.

Acknowledgements

We would like to acknowledge the contributions of the Bevalac operators to the long flattop project. Several years of development work was needed to advance our knowledge of spill structure and

Bevalac systems to the point where the long flattop could be implemented and used effectively. Bevalac operators contributed ideas, expertise, effort, and their knowledge of all the Bevalac systems. This was invaluable. We would like especially to thank Sue Daly and Don Cowles, who ran the machine and contributed greatly to the long flattop beam tests.

We also gratefully acknowlege the assistance of the MG operators, and the enthusiastic, extremely competent assistance of the EM shop personnel.

Appendix A: Magnet Testing and Protection

It was necessary to check the IPB and EPB magnets to make sure that the power levels for the long flattop would not overheat the magnets. With the exception of XM1, a septum magnet, all of the magnets are thought to heat on time scales much longer than a single Bevalac pulse. So the quantity which is relevant is the rms power level for a pulse, $I^2_{rms} R$, except for XM1 (heating time for XM1 $\approx$ 1 sec). The spiller perturbation magnets, P1, P2, S1, and S2 are cooled by liquid nitrogen, while the rest of the magnets are water-cooled.

The specifications for the long flattop project required running flattop lengths up to 10 seconds for fields up to 9.2 kG. The magnets were all checked for form factors (see Eqs. 1 and 2) up to 0.92 for the current profile of Fig.1. This is the main magnet current profile for a 10 second flattop at 10 kG and 4.6 pulses per minute. It is important to note that this is only approximately correct. Though the magnets are turned on at the same time as the main magnet, in general they come to field before the main magnet. This can increase the rms power by about 7%. [Note that if the TOAD feature is used, this will not occur - see Section IIIB.] However, none of the magnets are within 7% of their power limit. So the tests were not repeated.

The specifications for all magnets were first checked for form factor equal to 0.92 by Jim Halliwell and Steve Abbott, given maximum currents provided by J. Kalnins. The maximum currents were taken from all tunes on record. The currents assumed for each magnet are shown in Table 3, and J. Halliwell's notes, including resistances and power ratings for magnets, are in Table 4.

Table 3

Magnet	Maximum Current Assumed (Amps)
XM1	1020
XM2	2030
XM3	1605
XQ3A	1090
XQ3B	1225
XQ4A	2450
XQ4B	2450
XM4	recently became DC
X1Q4A	1559

X1Q4B	1575
X2Q4A	1000
X2Q4B	1065
S1Q7A	1129
S1Q7B	1264
S1M4	2386
S1M5	907

Checking the specifications showed that all magnets would be operating within acceptable limits, with the possible exception of XM1, XM2 and its choke, S1M4, P1, and S1. S2 is no longer used, and it was decided that P2 was not necessary. XM1, XM2, S1M4, S1, and P1 were then tested under the operating conditions just mentioned--current used at 10 kG main field, form factor of 0.92. In the case of XM1, the temperature of each individual coil was monitored. S1M4 and XM1 had no difficulty. The choke on XM2 was replaced by a large quadrupole of similar inductance to the old choke, and a booster pump was added to the XM2 cooling to avoid overheating.

When there is no beam, the current in S1 goes to 240 A (its maximum current) and stays there for the length of the S1 gate. Since S1 is in the spiller feedback system, and its current depends on the P1 current and operating conditions, it is hard to set a current at which S1 should be tested. Therefore we chose to be conservative and test S1 with a form factor of 0.92 and 240 A current. P1 was tested at 160 A. For these conditions, there were over-temperature trips, usually involving LN circuit 10 (S1). Whether or not trips occurred depended on the initial conditions of the LN valves and circuit temperatures. During these tests it was observed that there was about a 20 minute delay for heat to reach the temperature sensors-- when the magnet current is shut off, for instance, the temperature at the sensor continues to rise for about 20 minutes. This gives the feedback system quite a delay to cope with. Since trips were occurring, it was decided (Don Hunt) to increase the pressure drop across the LN circuits, thus increasing the gain and cooling capacity of the system. When the pressure drop was increased to about 19 psi, a test showed the system capable of handling the heat load for the long flattop. However, there was only time for one test, and given the dependence of the results on initial conditions (in a manner poorly understood at this time), it is not absolutely certain that this pressure drop is adequate. The test that was done had initial conditions which seemed very close to the conditions under which thermal trips had occurred in previous tests. In order not to change the rest of the LN system, the circuits (10 - 15) which cool S1 and P1 have now been vented to the atmosphere, giving only these circuits a pressure drop a little above 20 psi. This configuration was tested during the week of 8/30/92.

XM1 and XM2 were protected by time-overcurrent protection. This posed a problem for the long flattop, since increasing the gate length for the magnets increases the product of time and current more than it does the rms power. These magnets were tripping at allowable power levels. This could not be fixed by just changing the time overcurrent limit, since the magnets would then be inadequately protected for short flattops. The problem is that rms power does not scale like the product of current and time. When it was discovered that XM1 heated on a time scale of about 1 second-- heating was essentially instantaneous-- it was decided to set a simple current limit on this magnet. XM2 was given protection based on average power, plus a current limit. A time overcurrent protection circuit was also added to each. The time overcurrent protection at this time has high limits, and is only meant to insure that if the magnet is left turned on for long times it will shut itself off. Tom McGathen designed the new XM1, XM2 protection, which is documented in Engineering Notes with code BU4100 and serial 7290 (XM1) and 7291 (XM2). A Description and Instructions note also has been written (14Y5221).

Halliwell

Table 4.

	MAGNET	PULSED Y / N	RESISTENCE Ω (RS-value from Rw)	MAX KW	I max operating taken from tune sheets for 12575 operation *	I operating @ 10KG scaled from 12575 column	Irms = Iop x FF @ 10sec FT & For 4.8 PPM FF = .926	I_{rms}^2 x R : KW @ 10sec Flat zone 4.8ppm	NOTES: * Rounded off to the high side. @ FF for Bev 12575 oper at 10ppm @ 1.5 sec Flat Top = .667
	XM1	Y	.051 (RS)	36.5kw (see attached sheet)	1100 A	880	814	34kw	KW in with STD Bev 12575 ---- = 27KW
	XM2	Y	.0092 Hot / .00772 (RS)	24KW @ 1.9GPM / 45KW @ 3.6GPM	2360A	1888	1748	28kw (Hot R)	KW in with STD Bev 12575 → = 19KW. Flow 2.8GPM Trip off 1.5GPM measured - would allow 35KW for 80°C Hot spot design rating. UCID 1366
	XM3	Y	.022	37 kw +	1900A	1520	1407	44kw	KW in with STD Bev 12575 = 34KW. + This power give a 17.4°C Rise in coil Temp @ 8.6GPM Flow. Max conductor Temp 60°C. See UCID 1802
	XQ3A	Y	.048	36.4kw +	1350 A	1080 A	1000	48 KW	+ This power gives a 26°C rise in Temp of coil. Considering H_2O Temp = 40°C worst case. Coil Temp = 66°C. See UCID 1803
	XQ3B	Y	.048	36.4kw +	1450 A	1160 A	1074	55.4kw	+ " " " See UCID 1803
	XM3V	N	.0348 (RS)	NA	NA	NA	NA	NA	
	XM4V	N	NA	NA	NA	NA	NA	NA	
8QB32	XQ4A	Y	.034	245kw	Δ	?			Δ could not find a 12575 Tune which used XQ4A
8QB32	XQ4B	Y	.034	245kw	Δ	?			Δ could not find a 12575 Tune which used XQ4B
	XM4	Y	.123 (RS)	48kw	627A	501	DC	30kw	Designed for pulsed operation but is running DC at this time. I = 627A pulsed for operation - Discussion with Eng. It was stated that magnet could run DC at this level
8QB32	X1Q4A	Y	.034	245kw	2050 A	1640	1518	78kw	
,B32	X1Q4B	Y	.034	245kw	2100 A	1680	1555	82kw	
	X1M55	N	NA	NA	NA	NA	NA	NA	
8QU32	X1Q5A	N	.034	245kw	NA	NA	NA	NA	
8QN32	X1Q5B	N	.034	245kw	NA	NA	NA	NA	
	X2M55	N	NA	NA	NA	NA	NA	NA	
8QB48	X2Q4A	Y	.0364	203kw	1300	1040	963	38kw	
8QD48	X2Q4B	Y	.0364	203kw	1400	1120	1037	39kw	
8QL32	X2Q5A	N	.0325 (RS)	NA	NA	NA	NA	NA	
8QL32	X2Q5B	N	.0325 (RS)	NA	NA	NA	NA	NA	
	X2M7	N	NA	NA	NA	NA	NA	NA	
8QD48	S1Q7A	Y	.0364	203kw	1456	1164	1077	42kw	
8Q048	S1Q8B	Y	.0364	203kw	1607	1285	1190	53kw	
	S1M4	Y	.0082		3000	2400	2222	40kw	
5x84H	S1M5	Y	.148	376kw	1150	920	851	107kw	

Appendix B: Graphs for Optimizing Duty Factor

The graphs and tables below give theoretical limits. Regardless of what is printed below, the MG's should not be run for long flattops at high field (2 MG's) without checking carefully the 2-machine synchronization. DO NOT RUN if synchronization is not within normal limits-- shorten the flattop.

Heating of the Main Magnet may also limit the flattop on warm days, making the values shown in these charts unattainable.

Notes:

Spill length = flattop length - 0.5 sec.

RMS power limit = rms power of EPB and spiller magnets running 10 second flattop at 10 kG and 4.6 pulses per minute. All magnets have been tested to this limit.

Pulse length limit means that the flattop length + main magnet rise and fall times + 540 ms ≤ the pulse length.

Ten second flattop limit = no flattop length exceeds 10 seconds.

MG power limit = input power to each motor ≤ 3.3 MVA. 0.8 power factor assumed.

Duty Factor = spill length/pulse length.

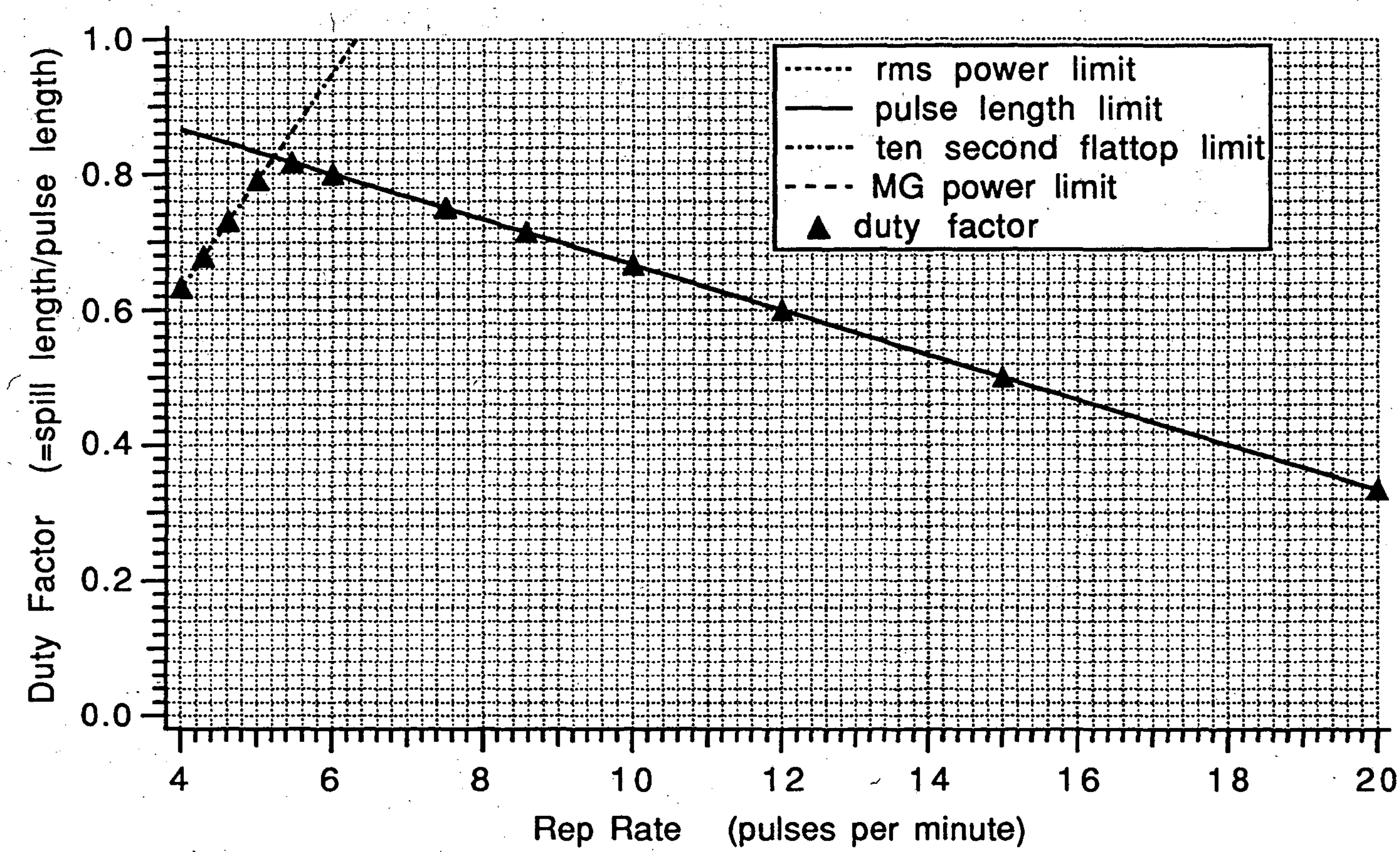
In the table, columns are:

rep rate (pulses/min)
duty factor (see above for definition)
maximum spill length permissible (seconds).

The graph for each main field value shows duty factor at the rep rates in the table (triangles), and the 4 limits described above (lines) if these limits are important at that field.

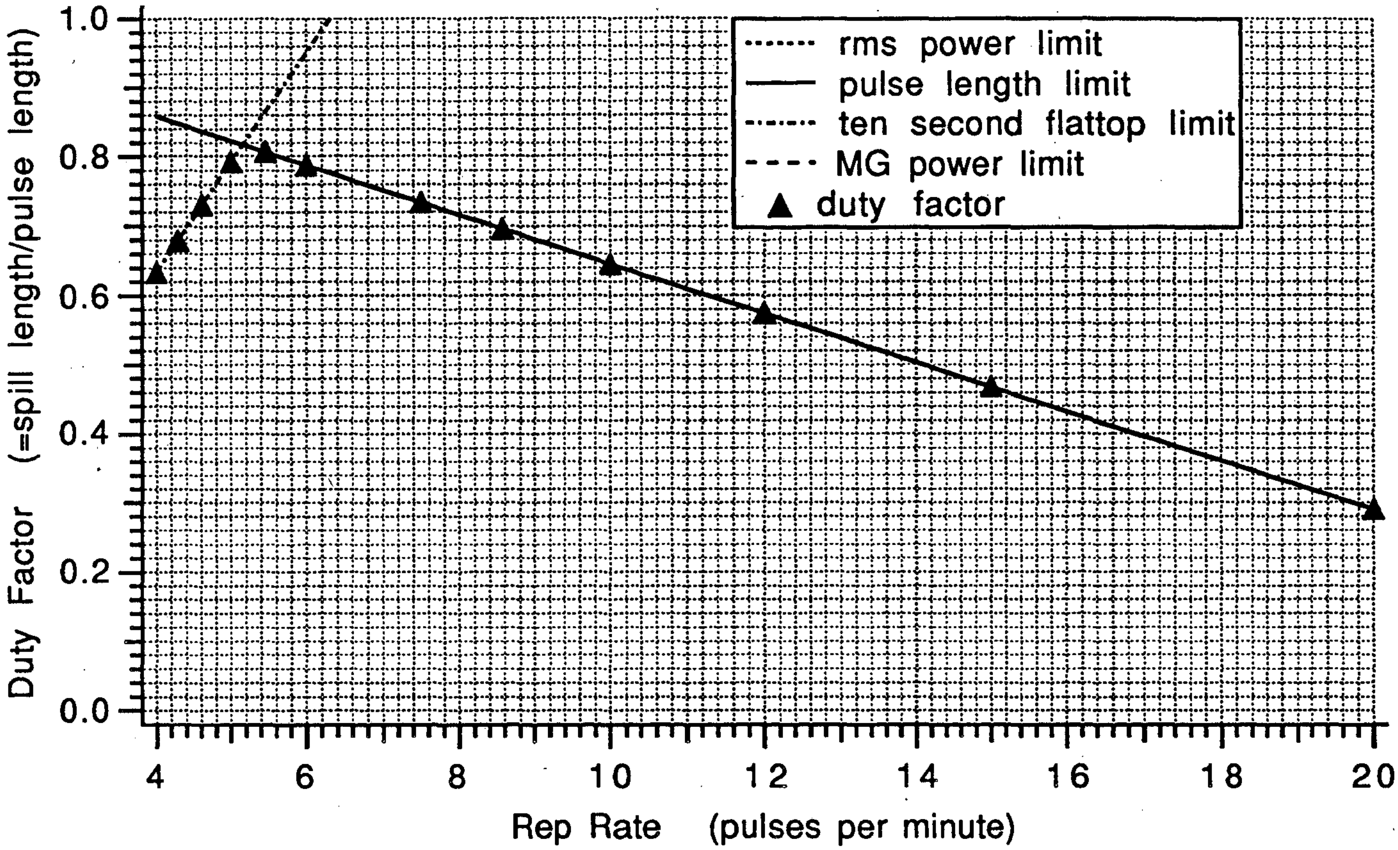
PLEASE GO TO NEXT PAGE

B=2535 Gauss - One MG Operation



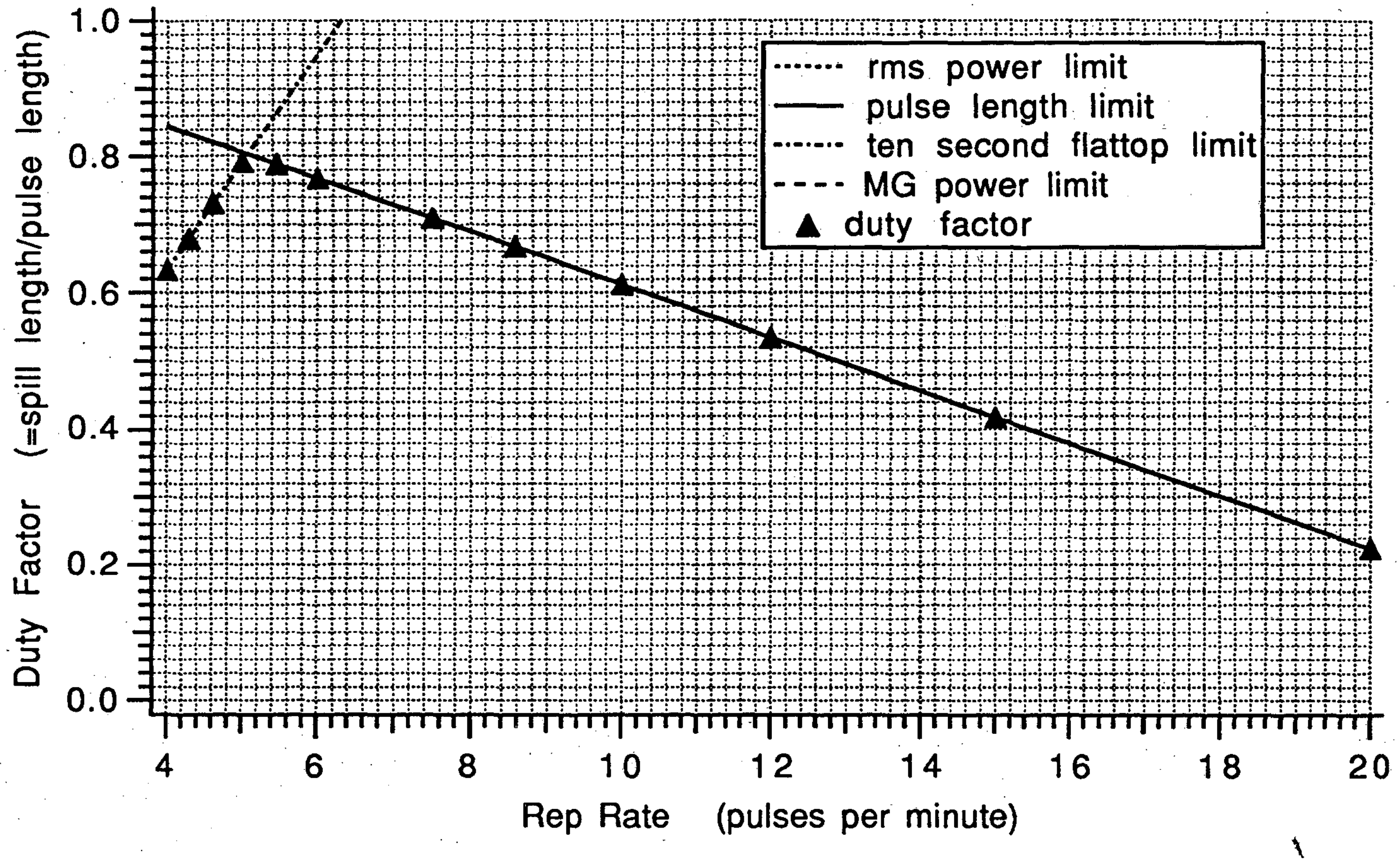
Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.730693	9.4998
3	5	0.79165	9.4998
4	5.455	0.818164	8.99905
5	6	0.799997	7.99997
6	7.5	0.749996	5.99997
7	8.571	0.714296	5.00032
8	10	0.666662	3.99997
9	12	0.599994	2.99997
10	15	0.499992	1.99997
11	20	0.333323	0.99997

B=2922 Gauss - One MG Operation

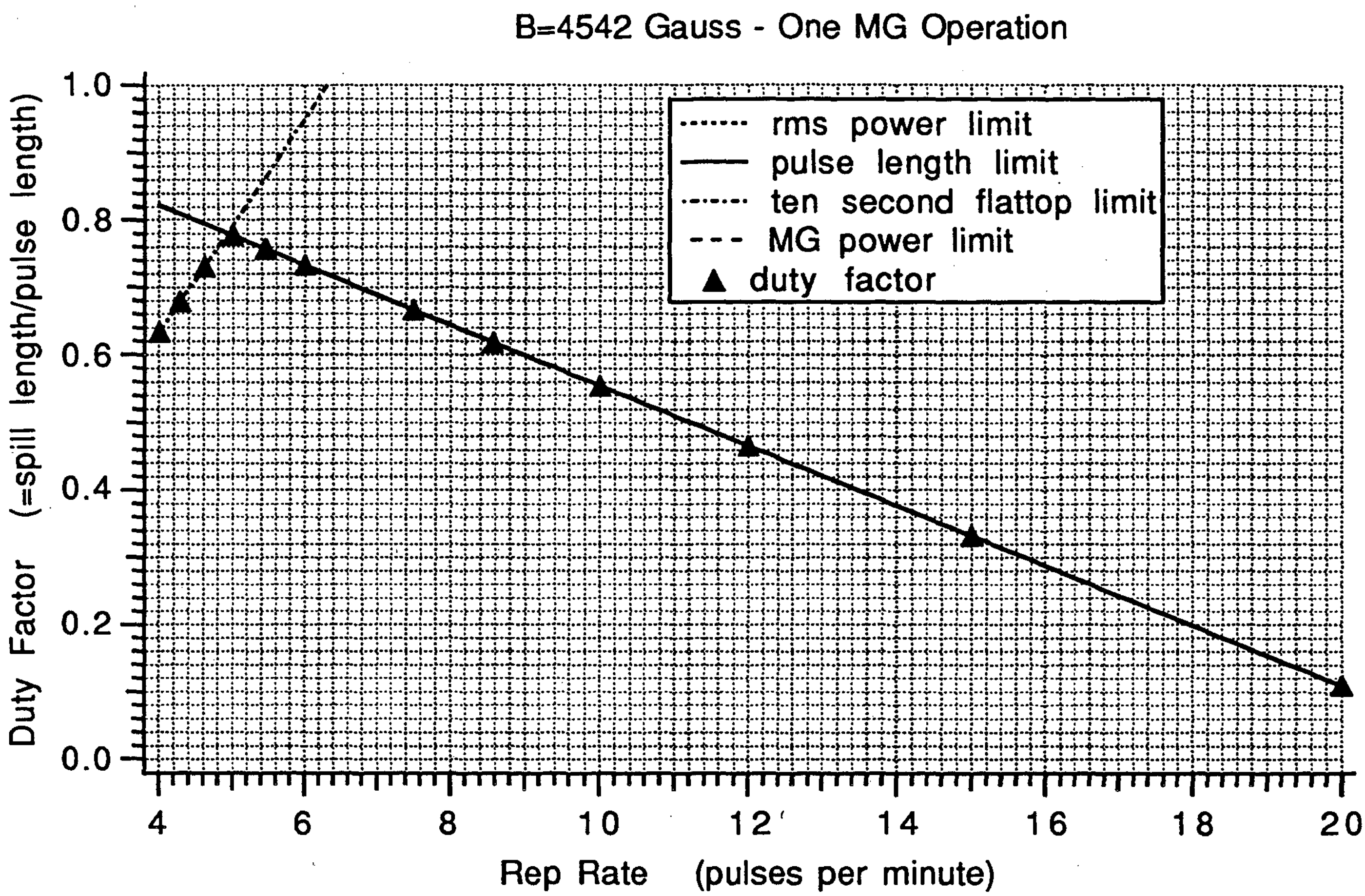


Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.730693	9.4998
3	5	0.79165	9.4998
4	5.455	0.806347	8.86908
5	6	0.787	7.87
6	7.5	0.73375	5.87
7	8.571	0.695729	4.87035
8	10	0.645	3.87
9	12	0.574	2.87
10	15	0.4675	1.87
11	20	0.29	0.87

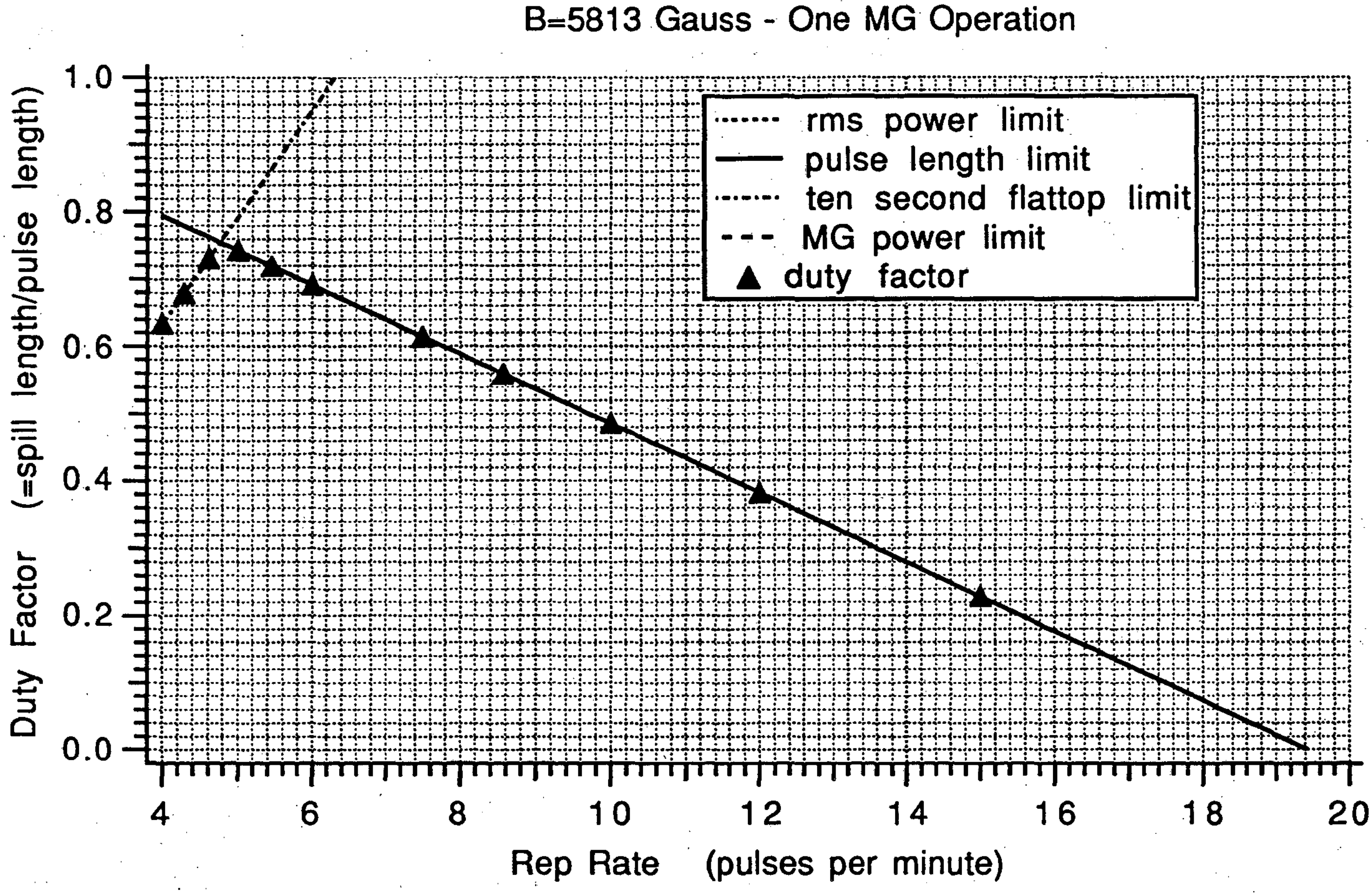
B=3528 Gauss - One MG Operation



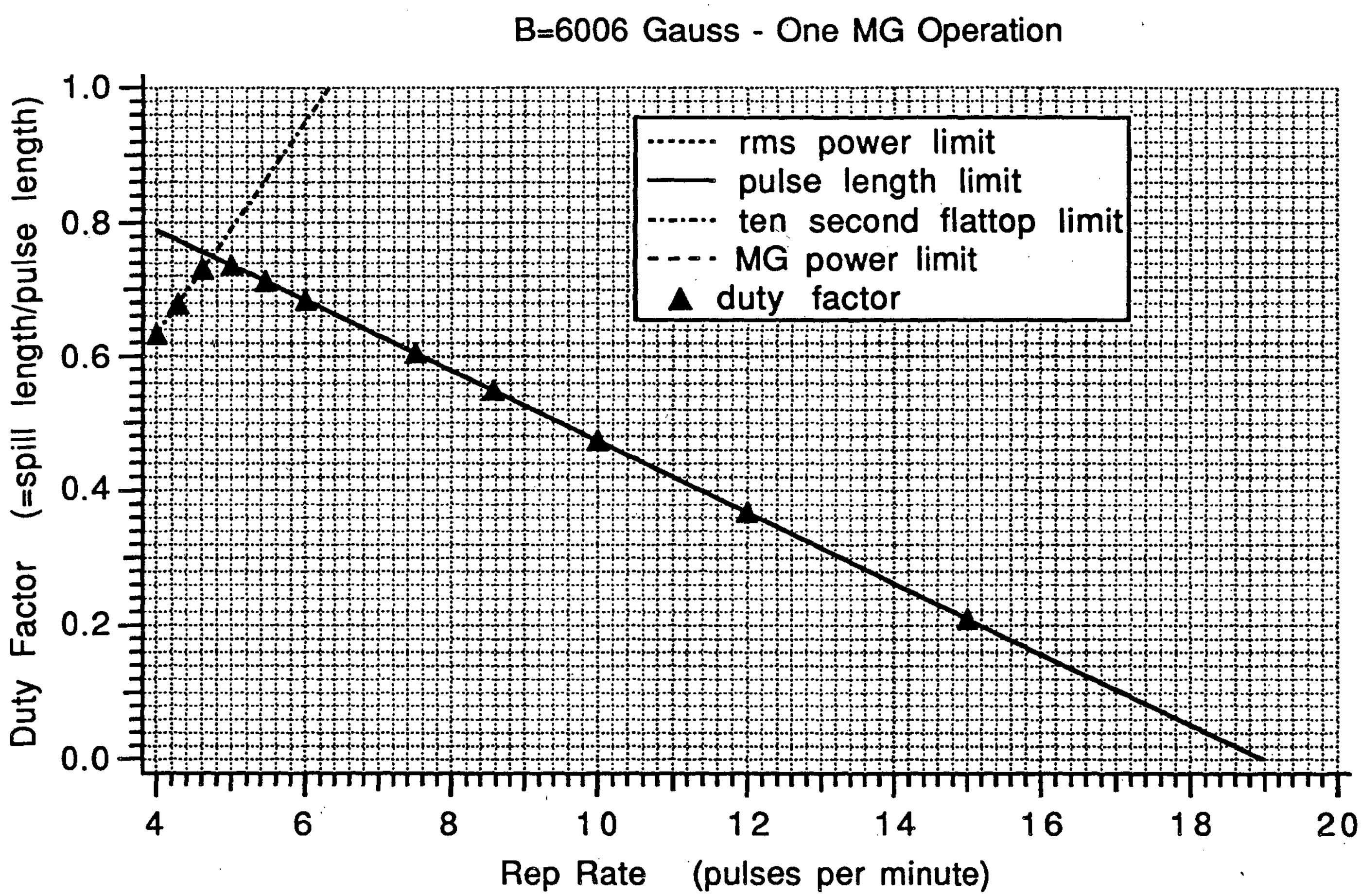
Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.730693	9.4998
3	5	0.79165	9.4998
4	5.455	0.788255	8.67008
5	6	0.7671	7.671
6	7.5	0.708875	5.671
7	8.571	0.667302	4.67135
8	10	0.611833	3.671
9	12	0.5342	2.671
10	15	0.41775	1.671
11	20	0.223667	0.671



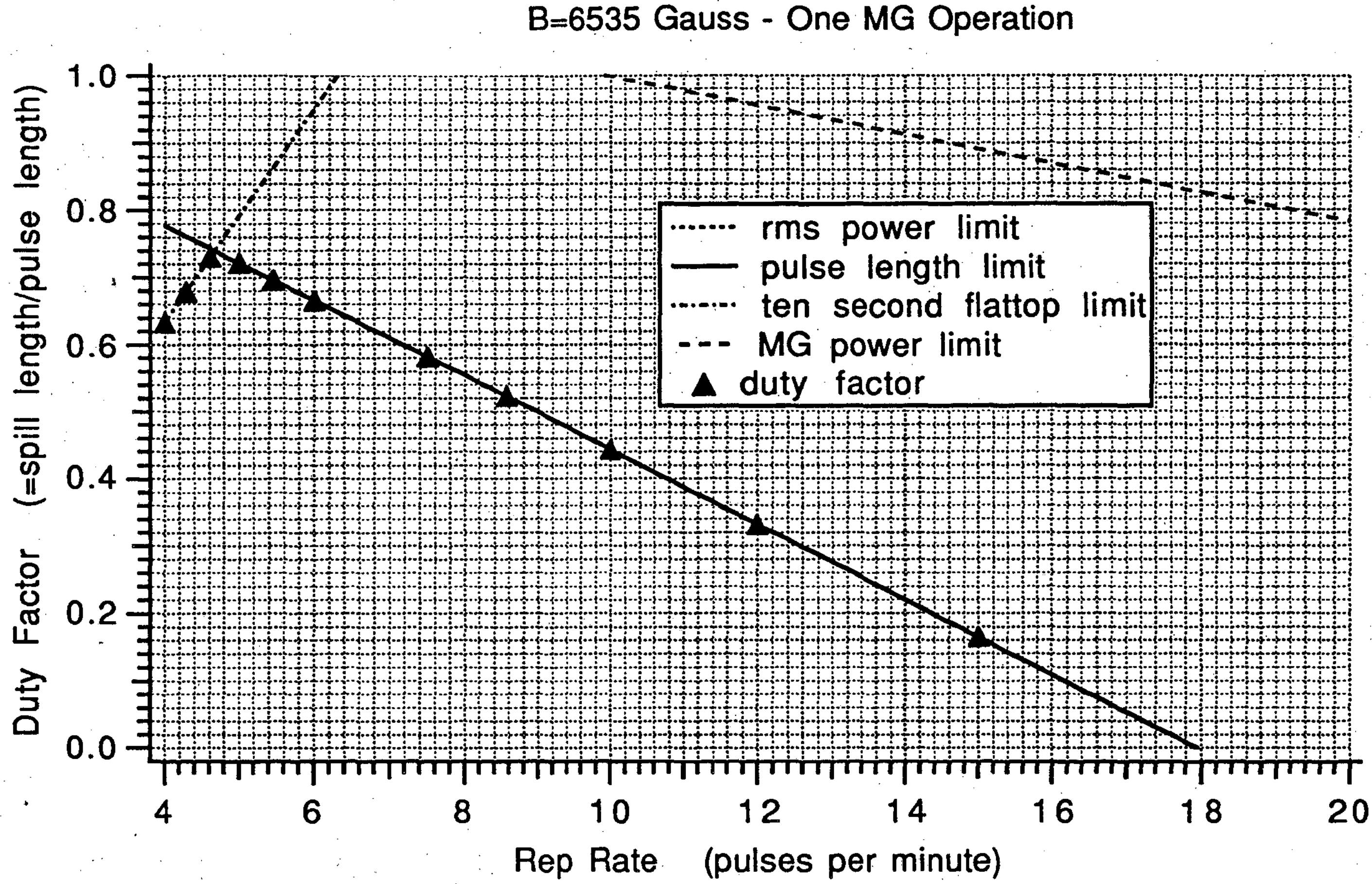
Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.730693	9.4998
3	5	0.777333	9.328
4	5.455	0.757071	8.32708
5	6	0.7328	7.328
6	7.5	0.666	5.328
7	8.571	0.618305	4.32835
8	10	0.554667	3.328
9	12	0.4656	2.328
10	15	0.332	1.328
11	20	0.109333	0.328
12			



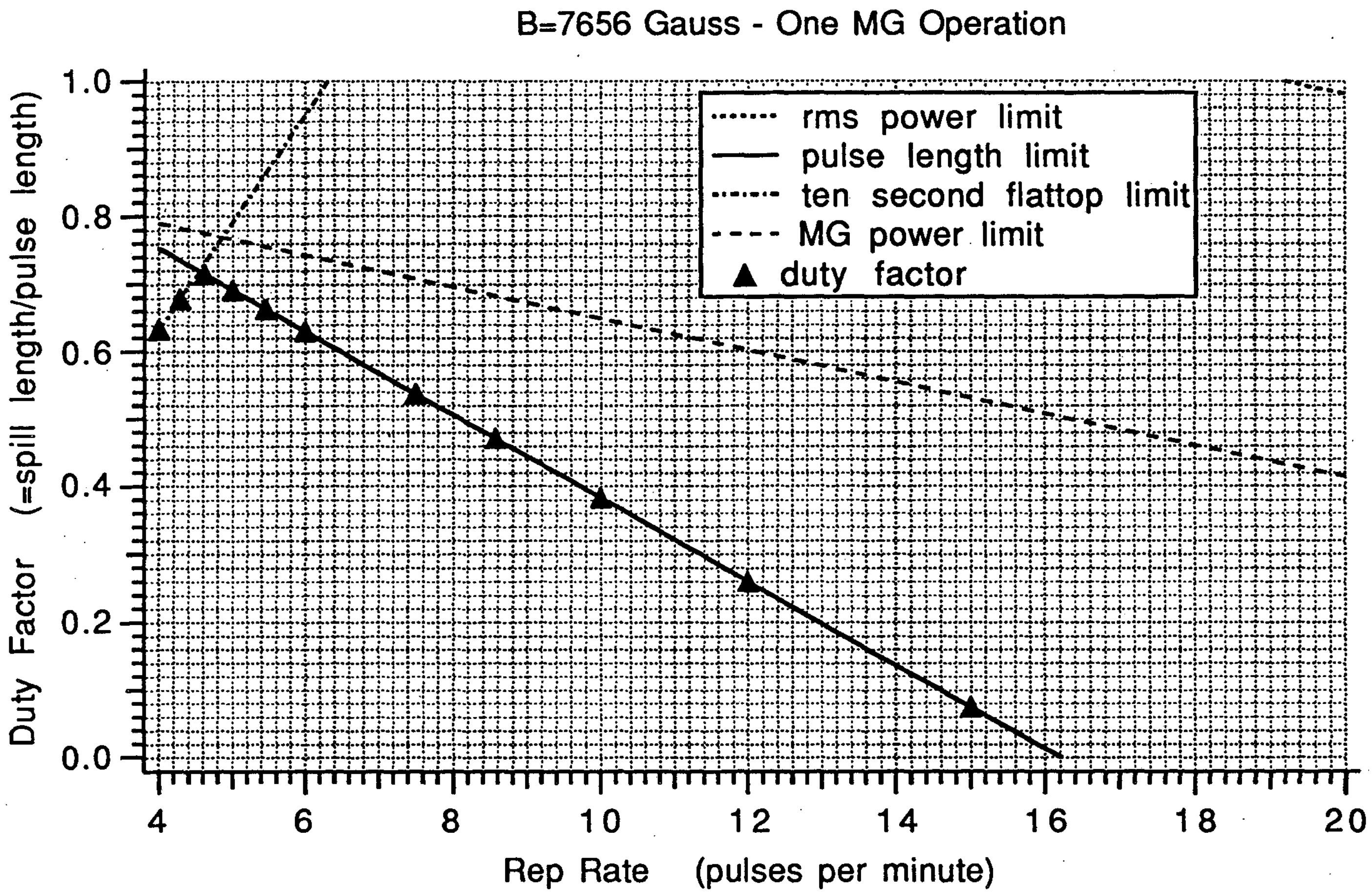
Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.730693	9.4998
3	5	0.742667	8.912
4	5.455	0.719249	7.91108
5	6	0.6912	6.912
6	7.5	0.614	4.912
7	8.571	0.558879	3.91235
8	10	0.485333	2.912
9	12	0.3824	1.912
10	15	0.228	0.912
11	20	-0.0293334	-0.0880001



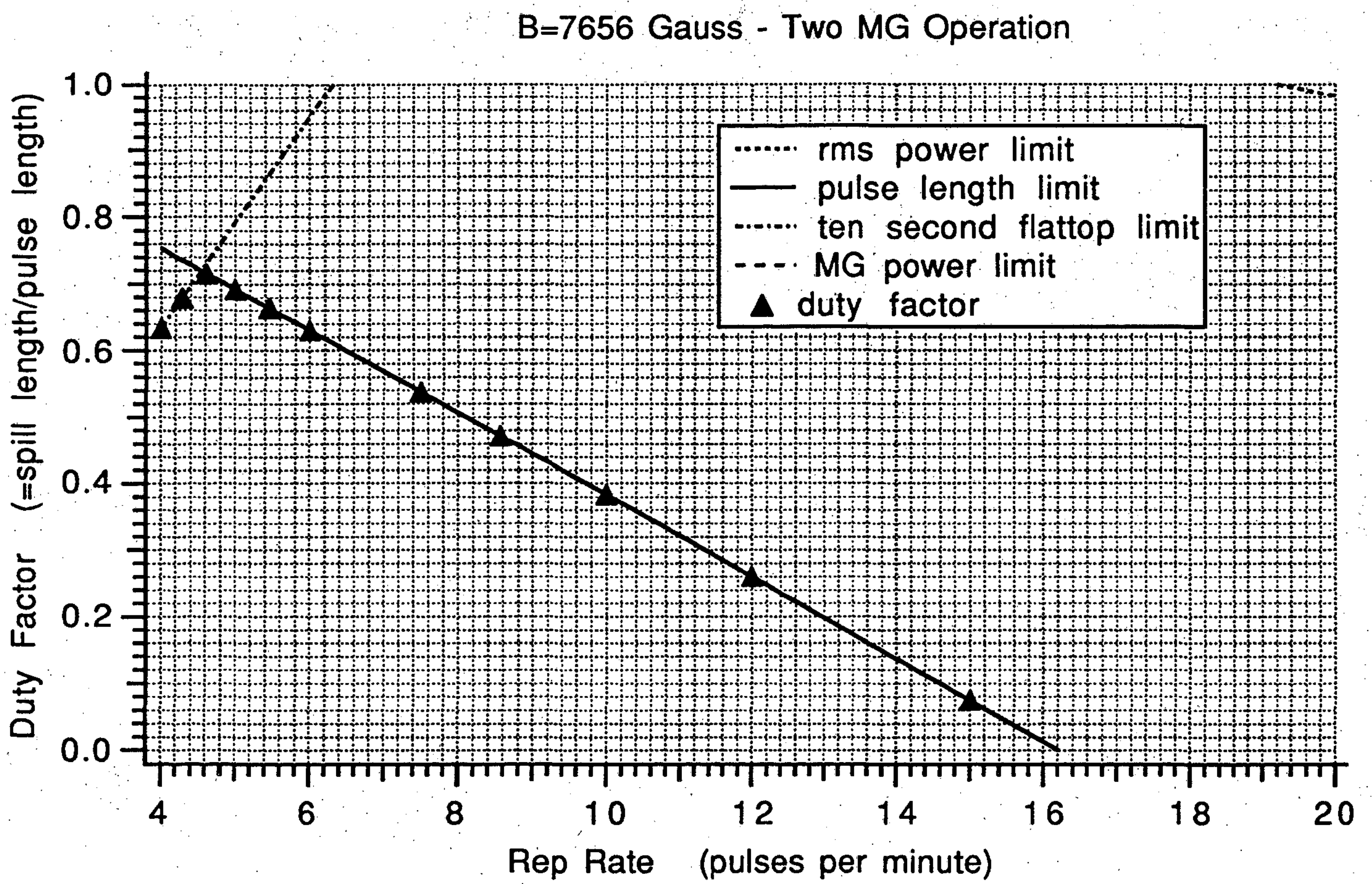
Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.730693	9.4998
3	5	0.736667	8.84
4	5.455	0.712703	7.83908
5	6	0.684	6.84
6	7.5	0.605	4.84
7	8.571	0.548594	3.84035
8	10	0.473333	2.84
9	12	0.368	1.84
10	15	0.21	0.84
11	20	-0.0533334	-0.16



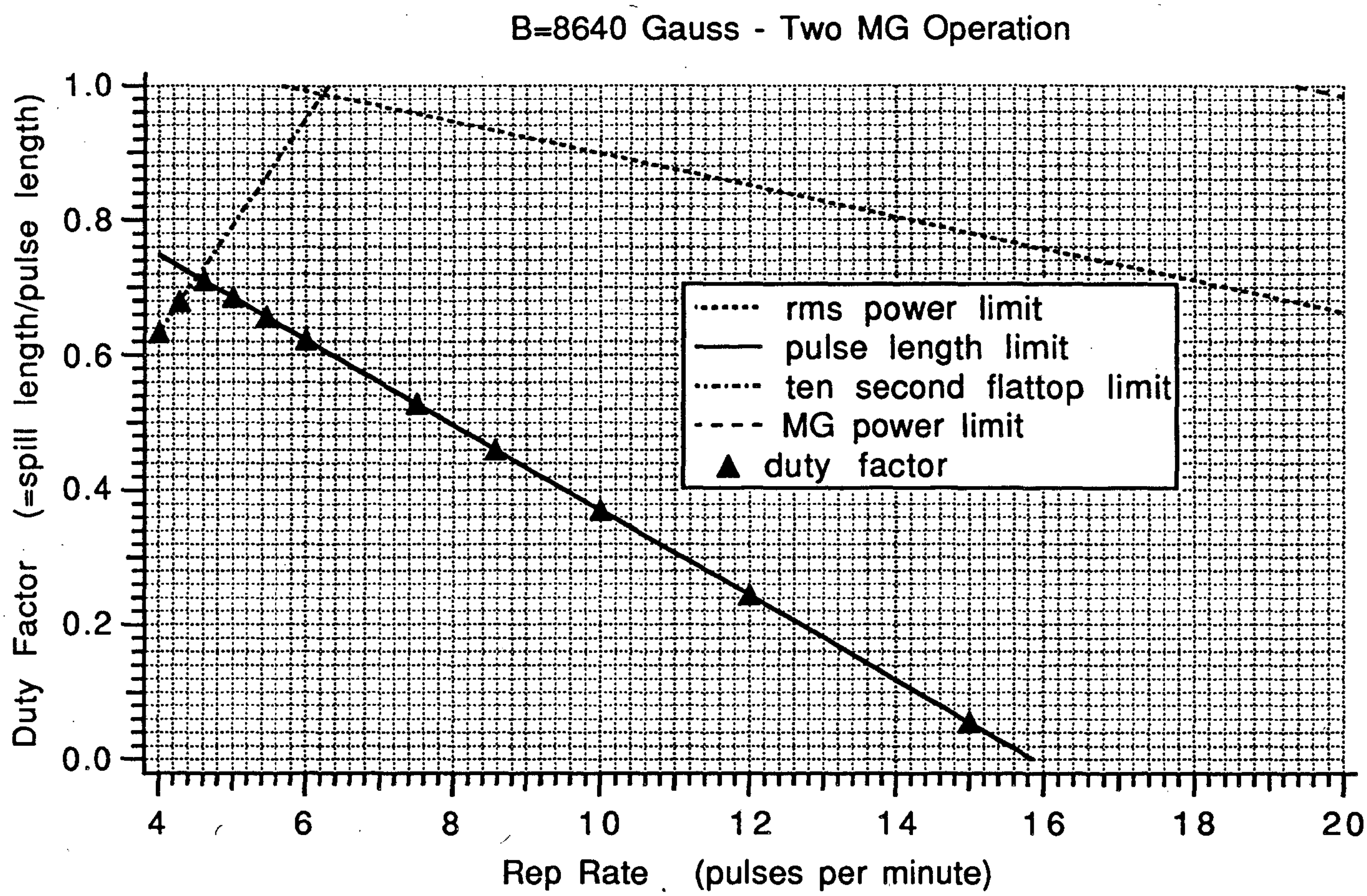
Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.730693	9.4998
3	5	0.7215	8.658
4	5.455	0.696157	7.65708
5	6	0.6658	6.658
6	7.5	0.58225	4.658
7	8.571	0.522595	3.65835
8	10	0.443	2.658
9	12	0.3316	1.658
10	15	0.1645	0.658
11	20	-0.114	-0.342



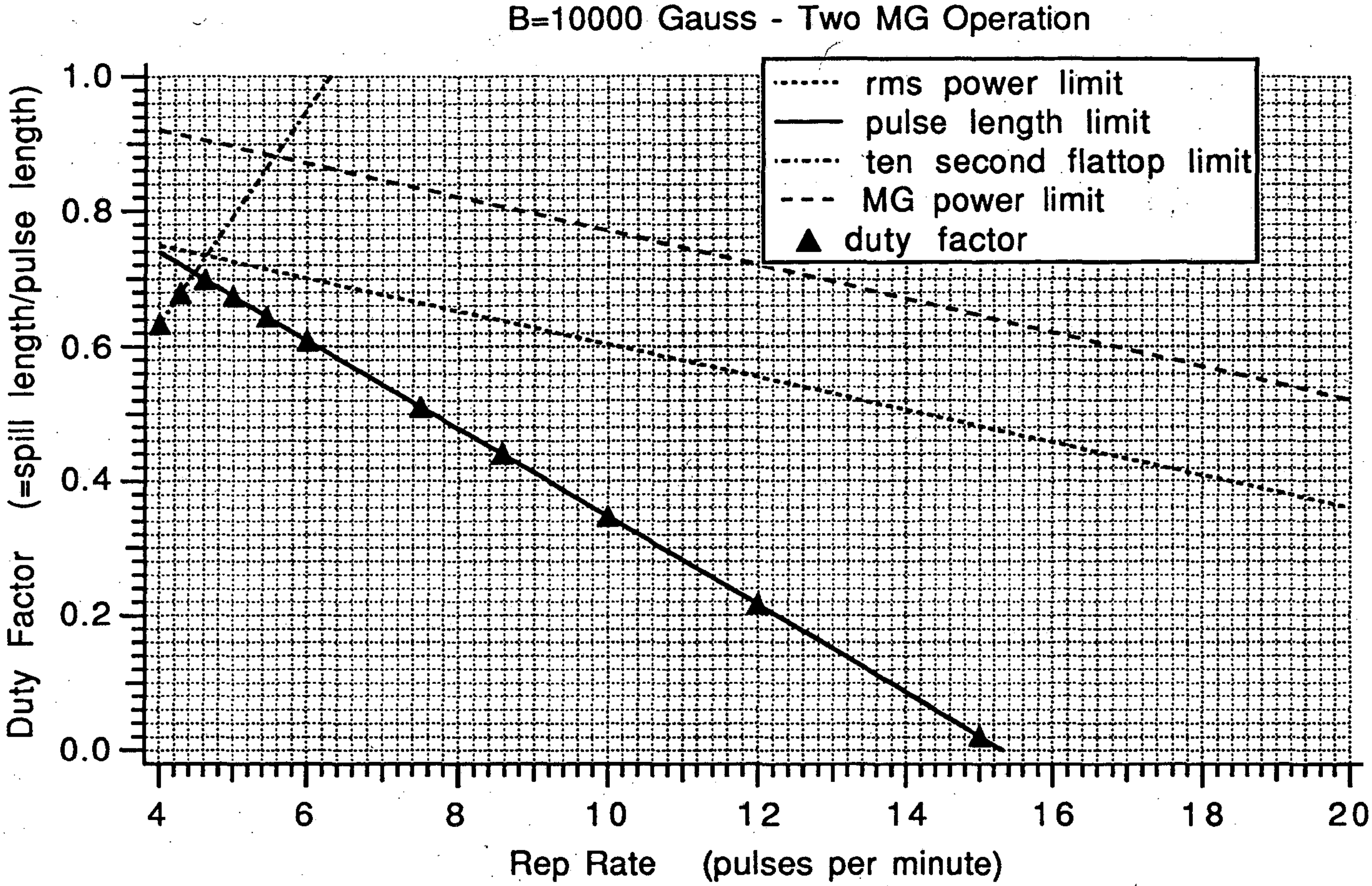
Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.715408	9.30108
3	5	0.691667	8.3
4	5.455	0.663608	7.29908
5	6	0.63	6.3
6	7.5	0.5375	4.3
7	8.571	0.471455	3.30035
8	10	0.383333	2.3
9	12	0.26	1.3
10	15	0.075	0.3
11	20	-0.233333	-0.7



Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.715408	9.30108
3	5	0.691667	8.3
4	5.455	0.663608	7.29908
5	6	0.63	6.3
6	7.5	0.5375	4.3
7	8.571	0.471455	3.30035
8	10	0.383333	2.3
9	12	0.26	1.3
10	15	0.075	0.3
11	20	-0.233333	-0.7

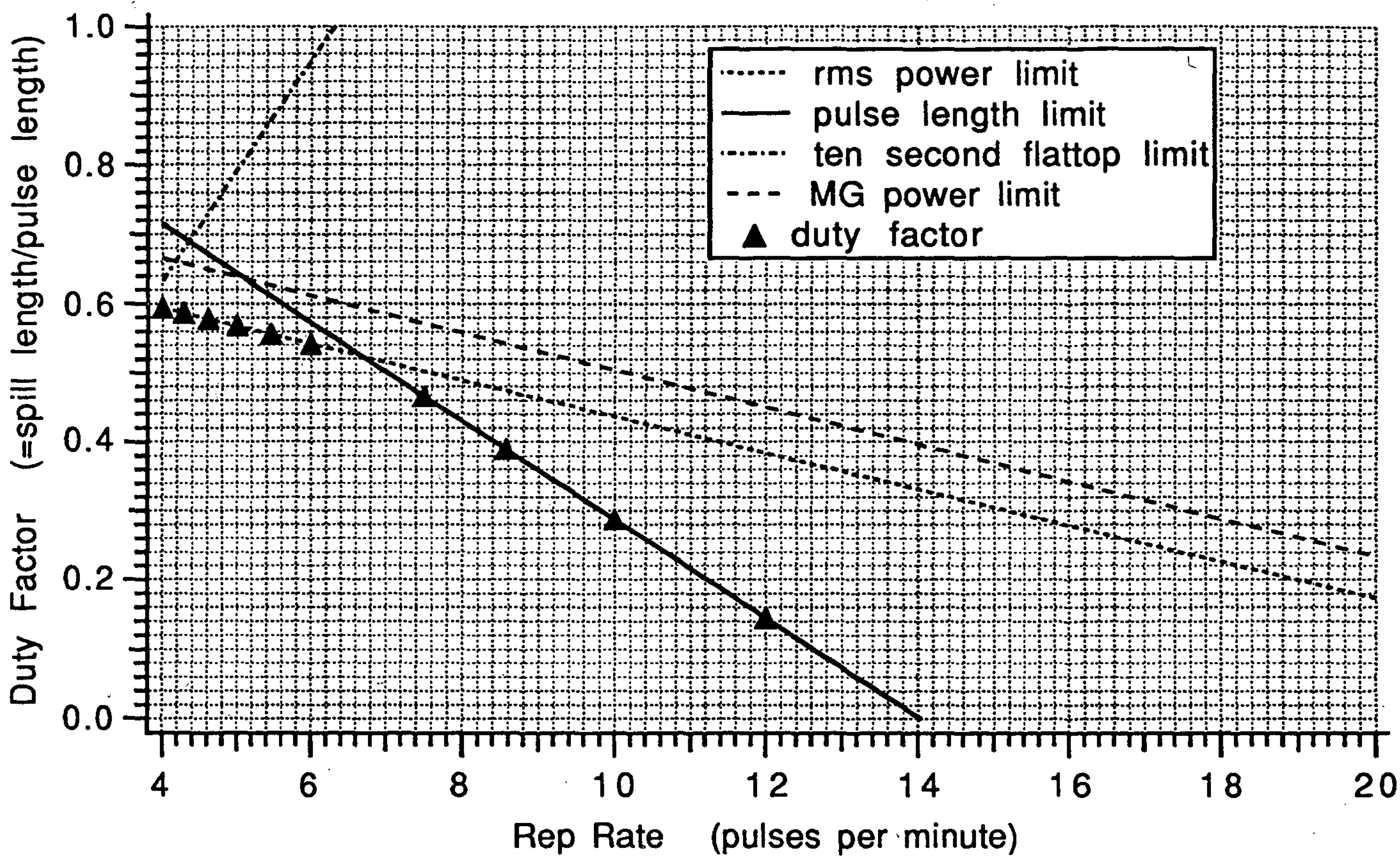


Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.709255	9.22108
3	5	0.685	8.22
4	5.455	0.656335	7.21908
5	6	0.622	6.22
6	7.5	0.5275	4.22
7	8.571	0.460027	3.22035
8	10	0.37	2.22
9	12	0.244	1.22
10	15	0.055	0.22
11	20	-0.26	-0.78

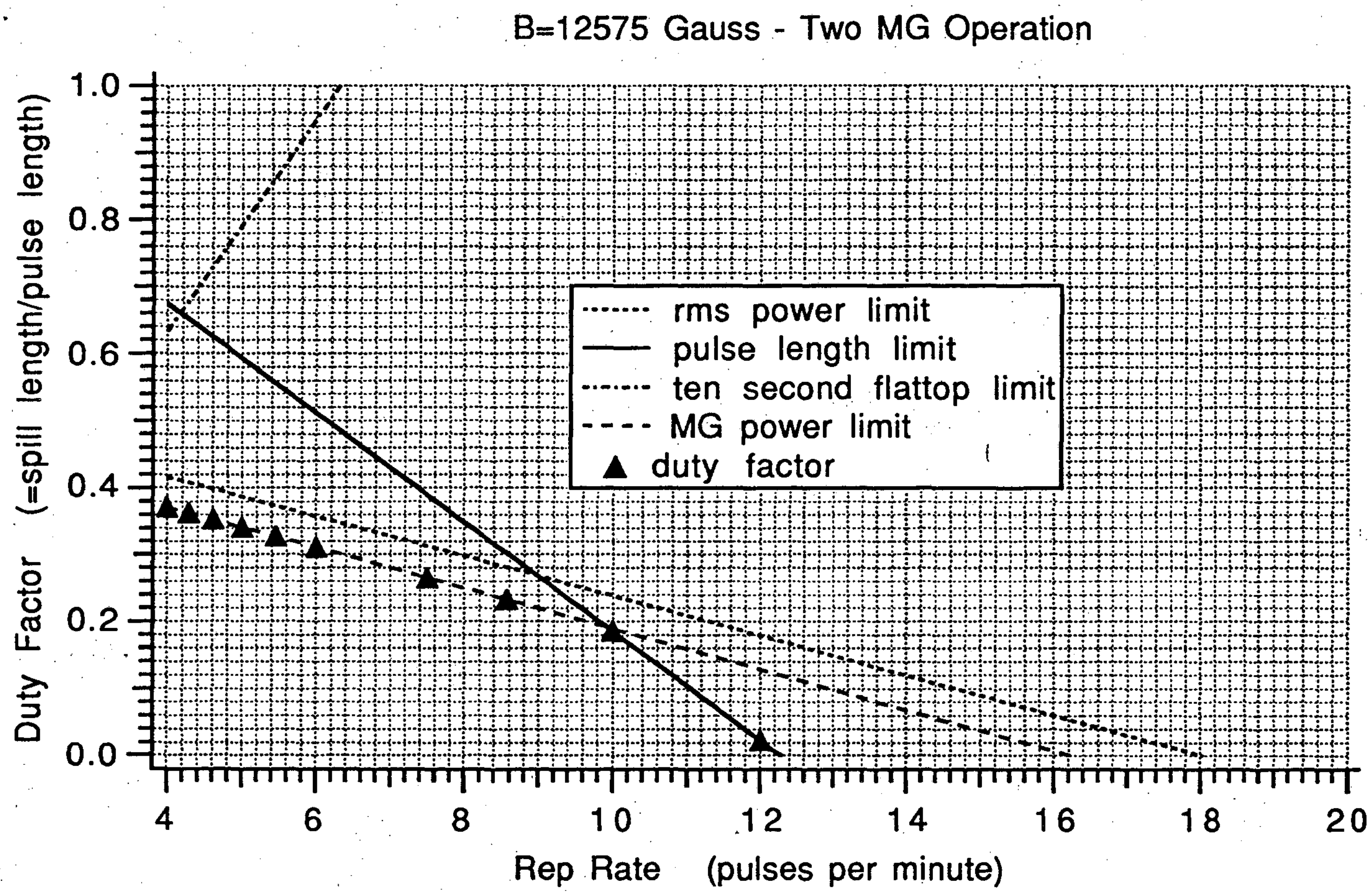


Point	reprate.y	dutyf.y	spill.y
0	4	0.63332	9.4998
1	4.286	0.678602	9.4998
2	4.615	0.698742	9.0844
3	5	0.67361	8.08331
4	5.455	0.643908	7.0824
5	6	0.608332	6.08332
6	7.5	0.510414	4.08332
7	8.571	0.440502	3.08367
8	10	0.347219	2.08332
9	12	0.216663	1.08332
10	15	0.0208288	0.0833154
11	20	-0.305562	-0.916685

B=11000 Gauss - Two MG Operation



Point	reprate.y	dutyf.y	spill.y
0	4	0.594256	8.91385
1	4.286	0.586731	8.21369
2	4.615	0.578075	7.5156
3	5	0.567945	6.81533
4	5.455	0.555973	6.11519
5	6	0.541633	5.41633
6	7.5	0.465482	3.72386
7	8.571	0.389153	2.72421
8	10	0.287309	1.72386
9	12	0.144771	0.723855
10	15	-0.0690361	-0.276145
11	20	-0.425381	-1.27614



Point	reprate.y	dutyf.y	spill.y
0	4	0.371304	5.56956
1	4.286	0.36263	5.07648
2	4.615	0.352651	4.58485
3	5	0.340974	4.09169
4	5.455	0.327173	3.59861
5	6	0.310643	3.10643
6	7.5	0.265148	2.12118
7	8.571	0.232664	1.62873
8	10	0.185833	1.115
9	12	0.023	0.115
10	15	-0.22125	-0.885
11	20	-0.628333	-1.885

Appendix C: 10 kHz Oscillator in Spiller

I. Introduction

This document describes an oscillator that was put into the spiller chassis by Mark Nyman, and first used in routine operation of the Bevalac in July of 1992. The purpose of the oscillator is to improve extracted beam spill structure. The concept and tuning of the device will be described below.

II. Concept

When the spiller feedback system increases the current in the S1 magnet, some beam becomes unstable. The amplitude of its betatron oscillation grows, and after about 100 μs the amplitude is large enough for particles to cross the septum and reach the feedback detector at F1. Because of this time delay in the feedback loop between the action of the magnet and the detection of its effect, the loop oscillates, turning the spill on and off at about 2.5 kHz.[1]

An oscillator has been inserted in the spiller chassis by Mark Nyman. It adds an oscillation at approximately 10 kHz to the S1 control signal, and therefore to the S1 current. If the amplitude is adjusted correctly, this turns the spill off and on at about 10 kHz--i.e., every 100 μs. It thus lowers the amplitude of the spill oscillations by turning the beam off earlier than it would be possible to do so if the spiller were to wait for the feedback signal. (Another way to see that the oscillation amplitude is lowered is to realize that since the spiller keeps the total amount of beam per second the same, if the spill comes out at 10 kHz rather than 2.5, the oscillations must have lower amplitude.) If the frequency is lower than the delay time frequency (10 kHz), the spikes in the spill are higher because the system waits longer to turn off the spill. If the frequency is higher, again larger amplitude spikes are seen. This may be because oscillations from S1 come too quickly, and a given oscillation may succeed in extracting beam destabilized by the preceding oscillation, as well as new beam. Or it may be that at the higher frequencies the magnet response is not good. We have had no

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[1] Technical note: The loop oscillates at the frequency where the delay in the loop is 180°, giving positive feedback. Since the integrator gives 90° delay, the oscillation occurs for a frequency for which 100 μs gives a 90° phase delay. This is about 2.5 kHz.

beam time to study this aspect of the system, so it is not completely understood.

Note that the normal spiller feedback system still controls the amount of beam spilled on the longer (> 0.1 millisecond) time scale. The oscillator adds an open-loop modulation of the spill on a faster time scale, in order to reduce the height of the spill oscillations.

III. Setup

The oscillator is on the integrator card in the spiller, and works only when the switch labelled "Signal Processing" on the front of the chassis is turned to the "Integrator" option. Note that it does not work with experimenter feedback, which requires the switch to be set to "3", or with a computer spill. At present there is no way to turn the system off, so if the switch is set to "Integrator", the oscillator is on. The "Spill Modulation" toggle switch has nothing to do with the oscillator.

We do not know at this time whether, or how much, the amplitude and frequency of the oscillator need to be changed when the running conditions (in particular, the main field value) are changed. Experience at present, and measurements of the delay time at different fields, indicate that the frequency does not need adjustment. If the system does not seem to be effective, it may be because the beam is located at an extraction radius where S1 has trouble controlling the beam, rather than because the oscillator needs adjustment (see Section IV in this appendix). It is advisable to try changing the radius first, rather than to change the oscillator amplitude.

At present the only way to change the oscillator amplitude and frequency is to open the front of the spiller and turn the two potentiometer screws which adjust them with a small screw driver. Check with the EM's or Mark Nyman or a Bevalac electrical engineer for help. If tuning turns out to be necessary, knobs will be added. What follows is a description of how to adjust these parameters.

To adjust the oscillator, begin by displaying the spill and the S1 current on an oscilloscope on a time scale of about 0.2 ms per division. These signals can be obtained from the BNC connectors on the front of the spiller chassis labeled "Spill" and, for S1, "Spill Control". It is easiest to AC couple the spill control (S1 current) signal, since only the AC behavior is important here. You should see the 10 kHz oscillation in both signals. Adjust its amplitude until it is big enough to turn the spill on and off, rather than just modulating the amplitude a little (see Fig. 1). As mentioned above, if you are unsuccessful, it may be that the beam is at an extraction radius where S1 has trouble controlling the spill (see Section IV in this appendix). Try changing the extraction radius.

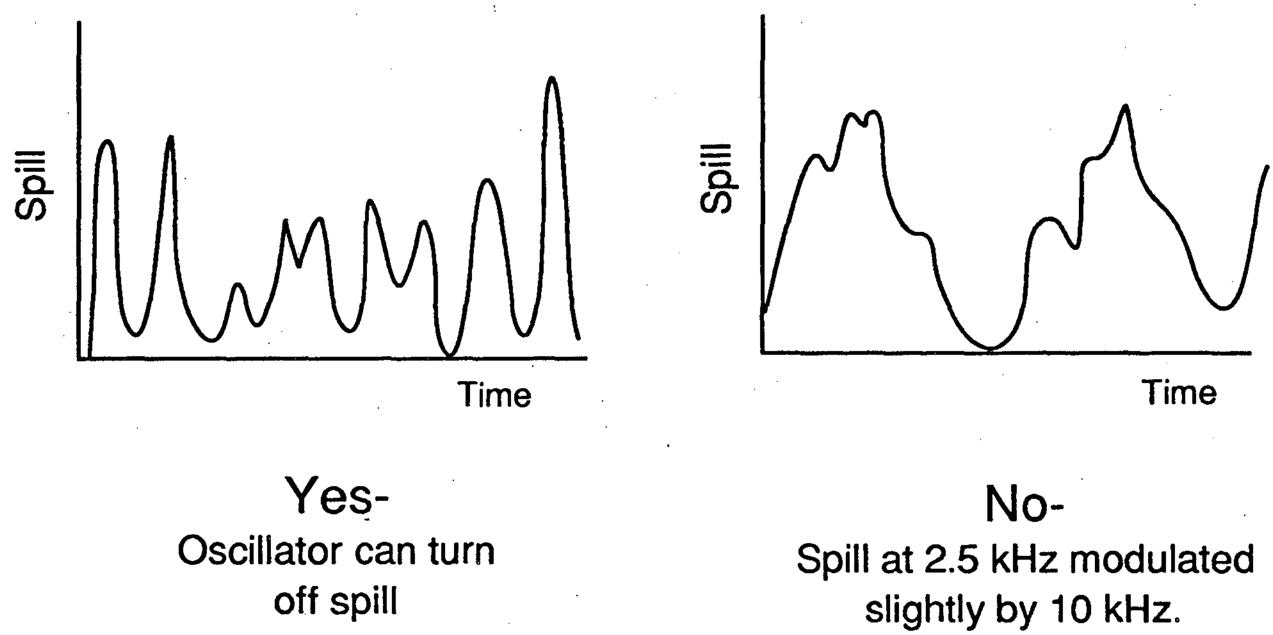

Figure 1

Next, adjust the oscillator frequency to give the minimum amplitude for the spill oscillations. The frequency should be around 10 kHz. When you are happy with the frequency, go back to the amplitude, and make sure that it is set at the value that minimizes the spill oscillation amplitude.

IV. <u>Effect of the Extraction Tuning on the Spill</u>

The extraction radius has a big influence on the effect of S1 on the beam, and therefore on the results derived from the oscillator. During one run (DLS in July, 1992), if the radius was too far outboard, while the spill structure looked very good (low amplitude) for the most part, in most spills several extremely high spikes were seen, which tripped the nuclear physics detectors. On the other hand, when the radius was too far inboard, the spill showed much more amplitude variation than one would like. It was necessary to change the radius while looking at the spill oscillations on an oscilloscope, in order to choose the radius which gave the best spill. This should be done each time extraction is tuned (with this system or with experimenter feedback), in order to optimize the spill for the experimenters.

P1 and the pole-face windings of course also have a major influence on the spill. To the extent it is possible without retuning the pole-face windings, P1 current should be set to give the best spill structure. In particular, S1 can not always control the P1 spill, with or without the oscillator, so P1 spill should be minimized. The P1 spill shows up at low frequency (~5 Hz), because this is our largest magnetic field ripple component. To check to see whether particular structure is due to P1 spill, turn off S1 and observe the spill.

Appendix D: Changes Made to the Bevalac to Implement the Long Flattop

An attempt is made in the following list to note all the changes to the Bevalac made while implementing the long flattop.

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Equipment	Changes	For more info refer to:
Control system	10 s flattop allowed (BMAG)	Section V Steve Lewis
	low level rf at flattop	
	wire chambers read to 10 s	
	mice timing done by computer	
	flattop length and rep rate limited to what will not overheat IPB and EPB magnets	
LN circuits 10 - 15	pressure drop increased by venting to atmosphere	Appendix A Don Hunt
XM2 choke	new choke	Appendix A Harvey Oakley, Blair Jarrett
XM2 cooling	booster pump added	Appendix A Steve Abbott
XM1 protection	changed to current limit from time overcurrent	Appendix A Tom McGathen

XM2 protection	changed to average power rather than time overcurrent	Appendix A Tom McGathen
SEM	time constant increased	Roger Dwinell, Ed Perry
RF	attenuators added to rf gating chassis so that rf amplitude can be lowered during flattop	Don Howard, Roger Dwinell

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