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The Bevalac Long Spill*

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Abstract

The Bevalac extraction time was increased from 1 to a maximum of 9.5 seconds, thus increasing the synchrotron duty factor and the data rate for experiments by a factor of 2-3, depending on the magnetic field. This slow rate of extraction required improved control of beam time structure, since magnet ripple remained approximately constant while the spill rate was decreased. Measurements of spill structure for the long spill are presented. Changes made to the accelerator systems are described, as well as tuning procedures found to be necessary, and the ultimate hardware limits found for the spill length.

I. INTRODUCTION

One measure of the efficiency of a synchrotron is the "duty factor", i.e., the percent of the pulse cycle time during which beam is being extracted for the use of the experimenters. Until July of 1992, the duty factor of the Bevalac ranged from 17% at full field (12575 G; 2.09 GeV/amu for Z/A=1/2) to 25% at low field (2500 G; 0.161 GeV/amu for Z/A=1/2). The normal pulse cycle included 1-1.5 seconds for extraction. As described in this paper, in July the timing cycle was changed so that for all but the highest magnetic fields the beam could be extracted for up to 9.5 seconds, with the rest of the cycle unchanged. This increased the duty factor to 34% at full field, 60% at 10 kG, and 80% at low field-- a factor of 2 - 3. The increase was reflected in an increased data rate for experiments performed in the last few months of Bevalac operation.

The circulating beam intensity was increased in proportion to the duration of extraction, so that average intensity remained the same. This meant that experiments already using the full intensity available from the source could not profit from the longer extraction time. In practice, this was not a problem for the experiments running when the long spill capability was available.

Ultimately the extraction time was limited by hardware constraints. These are described in Section II. In Section III we discuss measurements of the time structure of the extracted beam for the old (1 s) spill and the long spill, and describe changes made to the feedback systems which improved this structure .

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II. HARDWARE LIMITS TO THE EXTRACTION TIME

The stated goal of this project was to extend the extraction time to 9.5 seconds for main synchrotron fields up to 10 kG. However, every effort was made to increase the duty factor for all energies to the limit given by available hardware. As will be described below, the complete 9.5 second spill was not possible for fields at and slightly below 10 kG due to motor-generator synchronization, but the duty factor increases cited above were certainly sufficient to justify the project.

The limits to the extraction time were set by: (1) main magnet heating, (2) rms input power of the motor-generators powering the main magnet, and (3) synchronization of the motor generators. The first of these limits refers to the fact that on hot days the main magnet was not adequately cooled by the wind tunnel-fan-cooling tower system, and for any fields above 7 kG the extraction length could be limited by the main magnet temperature. However, given the climate, this occurred rarely.

Limits (2) and (3) refer to capabilities of the motor-generator system. The main magnet for the Bevatron was powered by two 12-phase half-wave-rectified motor-generator sets (MG's) with two 67 ton flywheels for energy storage. The input power for these motors was limited by fabrication specification to 3.3 MVA per motor, rms. A normal value for the power factor was 0.8, giving a limit of 2.64 MW per motor. It proved possible, using data obtained in 1949, to calculate quite accurately the rms power required of the motors. This included friction and windage losses, power losses in the rectifier ignitrons, I^2R losses in the motors and generators, and power loss in the main magnet. The motor power limit affected the possible extraction time for fields above about 12 kG, limiting extraction time to 5 seconds at full field.

For fields between about 8 kG and full field, synchronization of the two motor-generators provided an unexpected limit on the extraction time. At high fields (≥7600 G for 1 s spills), the power required for the main magnet exceeded what could be produced by one motor. The load was then balanced between the two motor-generators, with uncomfortable mechanical consequences if a sufficient imbalance occurred. Insufficient operating time was available to investigate the phenomenon, but somewhere between 8 and 10 kG this load imbalance began to occur for the longer extraction times. At 10 kG this effect limited the extraction time to 6.5 seconds. The load-balancing was performed by the "Kramer system", a system of two induction motor-generators used to supplement power from the public power line when flywheel speed dropped during peak power use. It was hypothesized that this system could not supply enough power for long pulses. Since the motors would slow at slightly different rates, this would lead to a phase difference between the two MG's, creating a load imbalance.

It should be noted that at low fields the extraction time could have been extended further than 9.5 seconds. This was not attempted, but the only limitations revealed by our work were the amount of charge available from the source, and, at very low extraction rates, the spill time structure. This latter factor will be discussed below. There is one precedent for near-dc beams in the Bevalac. As a prelude to construction of the PEP accelerator, beam was circulated in the Bevatron for 30 minutes without incident. However no extraction was attempted.

III. EXTRACTED BEAM TIME STRUCTURE

Increasing the length of extraction was expected to increase time variation of the extracted intensity. This is due to the fact that regardless of the length of the spill, the same fraction of the circulating beam, limited by extraction physics to approximately 25%, was extracted. Doing this over a longer time meant that a smaller percent of the beam (by almost an order of magnitude) was extracted per unit time, requiring much finer control of the magnetic field. For many experiments, degradation of the beam time structure could quickly undo gains due to increasing the synchrotron duty factor. "Count-rate-limited" nuclear physics experiments, for instance, use electronics or data acquisition systems which cannot tolerate intensities above a given value. Increases in the amplitude of beam intensity oscillations would necessitate decreasing the average intensity, to bring the highest amplitudes below this threshold. This could bring the data rate back to the values obtained with the old 1 second spill. Early trials with a low rate of extraction showed that for the Bevalac this did not occur-- though the spill structure deteriorated somewhat with lengthening extraction time, there was a net gain in projected data rate. However improvements in the spiller feedback system, described below, kept the quality of the spill somewhat constant as the extraction time was increased, enabling gains for the experiments commensurate with duty factor increase.

Beam extraction was accomplished using resonance extraction. Just before extraction the beam tune was brought close to 2/3 by a perturbation magnet, P1. A (mainly) sextupole winding, S1, on the same magnet then was used to drive orbit growth by ramping the sextupole, thus moving the unstable fixed points into the beam. Normally 20 - 30% of the beam could be extracted.

Variations in the intensity could be caused by time structure in the main magnetic field or the extraction (perturbation or sextupole) magnet fields. In practice, the currents of the extraction magnets could be better controlled, and measurements of the extracted beam intensity vs. time, to be described below, show that the main magnet ripple contributed most of the structure which was due to magnetic field ripple. Because of the large dispersion of the machine, ripple in the main magnetic field, $\Delta B/B$, as small as $\sim 2 \times 10^{-7}$ could produce bursts of beam [1].

Several feedback systems were in place to minimize magnet ripple. These included: feedback control of the generator voltage and phasing (effective for low frequency: 0-5 Hz) , LC filters across the main magnet (170, 354, 658, 1008, 1345 Hz), and the "Ripple Reduction" feedback system (10 Hz - 20 kHz). The Ripple Reduction system measured dB/dt using a one-turn loop in each quadrant of the machine, and made use of extra pole-face windings to compensate for field ripple. It should be noted that due to the load on the motor-generators, main magnet ripple did not occur at multiples of power line frequencies, but rather at multiples of a frequency somewhat lower which depended on the value of the main field. This is reflected in the filter frequencies given above.

A final feedback system directly controlled the beam extraction rate in order to minimize variation of the intensity. The "spiller feedback system" [2,3] measured extracted beam intensity vs. time using a scintillator and photomultiplier tube, then adjusted the current in the S1 magnet in order to keep the beam intensity constant. The bandwidth of this system was approximately 0-2 kHz. Though effective at these frequencies, the system actually introduced an oscillation into the extracted intensity at approximately 2.5 kHz, due to delay in the feedback loop. Beam destabilized due to an increase in S1 current required approximately 100 μs to reach the septum magnet and leave the synchrotron. Thus the information available to the feedback system about the condition of the beam was essentially delayed by 100 μs. As the control system began extraction, S1 current would rise until the intensity measured by the PM tube was at the right value, then attempt to stabilize the level. Due to the delay, the beam intensity would continue to increase (following the previous increase in S1 current), causing the feedback system to decrease the S1 current enough to actually stop the extraction. Thus the beam spill occurred in ~2.5 kHz bursts[1], modulated by lower frequency structure at harmonics of the MG fundamental. As noted in reference [3], very low frequency (~5 Hz) variation of the intensity was also seen, and traced to the voltage regulation feedback loop of the generators.

An improvement was made to the spiller feedback system by one of the authors (M.N.) which greatly improved its quality for experiments. As noted above, this was of particular importance for long spills, where the beam was extracted over several seconds. A 10 kHz oscillation induced in the S1 current by a malfunctioning power supply was observed to decrease the amplitude of the feedback oscillations in the beam intensity. So an open-loop oscillation at approximately this frequency was introduced into the S1 current. This had the effect of terminating the feedback oscillations in the beam intensity before the feedback system could, lowering the amplitude of the bursts. The beam then emerged with ~10 kHz structure rather than 2.5 kHz. It was found that varying the frequency of the applied oscillation

[1]Note: Oscillation occurs at the frequency where the delay =180°. Since the loop includes an integrator to produce the time average, which contributes 90° to the delay, the oscillations occur at 2.5 kHz, where 100 μs gives a quarter-period delay.

either up or down from the approximate frequency fortuitously applied by the faulty power supply increased the amplitude of the bursts. This is assumed to be because this frequency has a period equal to the information delay time in the loop. If the applied oscillation is at higher frequency, beam destabilized during one oscillation may add to the next burst. If the oscillation is slower, the system will not catch the intensity overshoot due to the delay. The optimal waveform for the oscillation appeared to be approximately a sawtooth.

The beam time structure was measured by two different systems, both using the signal from a scintillator-PM tube system at the first focus of the beam in the extraction channel. One system Fourier analyzed the signal (bandwidth $\leq$ 20 kHz), and the other sampled the signal for intervals of 0.5 s at 1 MHz. As a measure of beam quality, the ratio of rms to average intensity for each of the 0.5 s intervals was computed from the data obtained from the latter system. This will be referred to as the "spill duty factor", or SDF. Though very little time was available in the last months of Bevalac operation for making accelerator measurements, extensive data-taking was done over one two-day period (Sept. 15-16, 1992), and at other times experimenters were consulted as to the quality of the beam they received. The data quoted below derives from the measurements of Sept. 15, 16. The main field strength was 7650 G, or 1.05 GeV/amu for q/m=1/2.

The SDF varied with the tuning of the synchrotron. But it was not found to degrade significantly as the extraction time lengthened. For a 1 s extraction time the SDF was 1.6. At the beginning of the long (9.1 s) spill, the SDF was worse (2.3), though such an increase is more than compensated by the increased length of extraction. However measurements of 0.5 seconds at the middle of the spill produced an SDF of 1.5, and the SDF near the end of the spill was found to be 1.4. Thus in some average sense the time structure of the long spills was better than that of the 1 second spills, at least on the days when our measurements were permitted. This was born out, as mentioned above, by an increase in data rate for the experimenters at least commensurate with the increase in synchrotron duty factor.

Fourier analysis of the beam time structure revealed the usual components due to MG ripple below about 2 kHz, as described in reference [3], plus the ~10 kHz (actually, 8.8 kHz) oscillations inserted by the oscillation applied to S1, and harmonics of this frequency. Sidebands occurred for the 8.8 kHz structures and their harmonics whose spacing was given by the MG frequencies. The frequency domain data was examined to try to find some reason for the improvement in the time structure with time during the long spill. dB/dt due to the MGs, as measured by the dB/dt loops, actually increased during this time, both at harmonics and subharmonics of the MG frequency and for the ~5 Hz structure. Oscillations in the Ripple Reduction feedback system were somewhat less, but it is not at all clear that this can account for the improvement. Figure 1 shows the signal from the PM tube (in arbitrary units) vs. time for typical 5 ms intervals of spill. The upper trace is taken from the last third of the spill, and the lower from the first third. The difference in structure is notable. The improvement seems not to be due to the difference in the distribution function of the particles extracted at the beginning vs. the end of the spill, since a similar change in time structure does not occur for 1 s spills. It is possible that the increased field ripple, plus the slowing of the MG's due to the prolonged load, made the effect of the 8.8 kHz oscillation more favorable. As can be seen from Figure 1, at the end of the spill the S1 oscillation was not able to completely shut off the spill.

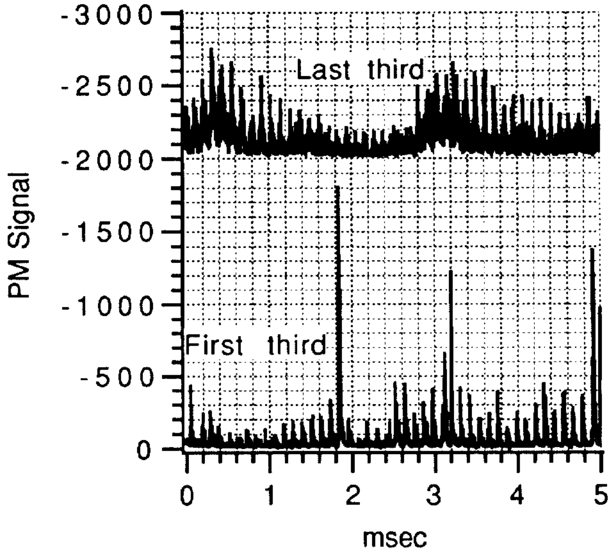

Figure 1. Photomultiplier signals vs. time showing extracted beam intensity from 5 ms of the first (lower trace) and third (upper trace) third of the spill. The upper trace has been offset by -2000 of the (arbitrary) units for clarity.

IV. SUMMARY

The maximum Bevalac extraction time was increased from 1 to 9.5 seconds for its last few months of running. This increased the synchrotron duty factor by a factor of 2 to 3 depending on the beam energy. Time structure of the extracted beam was as good or better than with the shorter extraction time. Due to the lack of time to study this phenomenon, the cause is not known.

V. REFERENCES

[1] J. Staples, private communication.
[2] M. Nyman et al., *IEEE Trans. Nucl. Sci.* **NS-32**, No. 5, 2177(1985).
[3] C.M. Celata et al., *Conference Record of the 1991 IEEE Particle Accelerator Conference*,, Vol. 3, pp.1401-1403.