

OPERATING EXPERIENCE WITH THE RESONANCE EXTRACTION SLOW SPILL CONTROL SYSTEM AT THE ZERO GRADIENT SYNCHROTRON\*

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Summary

Simultaneous resonance extraction to two proton lines became operational in spring of 1975. The spill quality was initially poor due to 100% structure in the two to six kHz range. This paper describes the empirical techniques developed to provide a smooth spill. These techniques consist of applying radial or azimuthal disturbances to the proton beam. It has been found that the most effective disturbing frequency depends uniquely on the beam momentum. Quite an array of new equipment had to be built for magnetic control of the unbunched beam. Brief descriptions of this equipment are provided.

Introduction

Both the extraction process, the magnet arrangement and the spill control system have been described before. The results previously presented concerning the quality of the beam turned out to be quite optimistic. Optimism is not unusual in the accelerator business.

We achieved satisfactory spill quality in 1975. It is the purpose of this paper to describe the empirical techniques which made the improvement. Due to the

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limited future of weak-focusing accelerators, these techniques may be of little general use. We have, however, noted similar problems in the literature.<sup>2</sup>

Protons from the Zero Gradient Synchrotron (ZGS) are supplied to two experimental areas which are 180° apart in reference to accelerator circumference. The extraction system which supplies beam to both areas simultaneously operates on a  $\nu_x = 2/3$  resonance. The component layout and the dynamics of the extraction process have been previously described<sup>1</sup> in some detail, so only a brief description will be provided here.

The ZGS has eight straight sections. Sextupole magnets are located in the SS-1 and SS-5 straight sections. Protons made unstable by these sextupole fields are intercepted by thin septum magnets in SS-4 and SS-8. Protons intercepted by each thin septum continue out through a four magnet extraction chain. Small dipole magnets which regulate the spill rate are located in the SS-3 and SS-7 straight sections.

Spill Control System

Intensity modulation of the beam is often called "structure." Structure is chiefly caused by the RF buckets, nonlinear radial distribution of the beam, and magnet field ripple on the main guide magnets, the pole face windings, or the sextupole magnets. At the ZGS, 85% of the radio frequency structure dis-

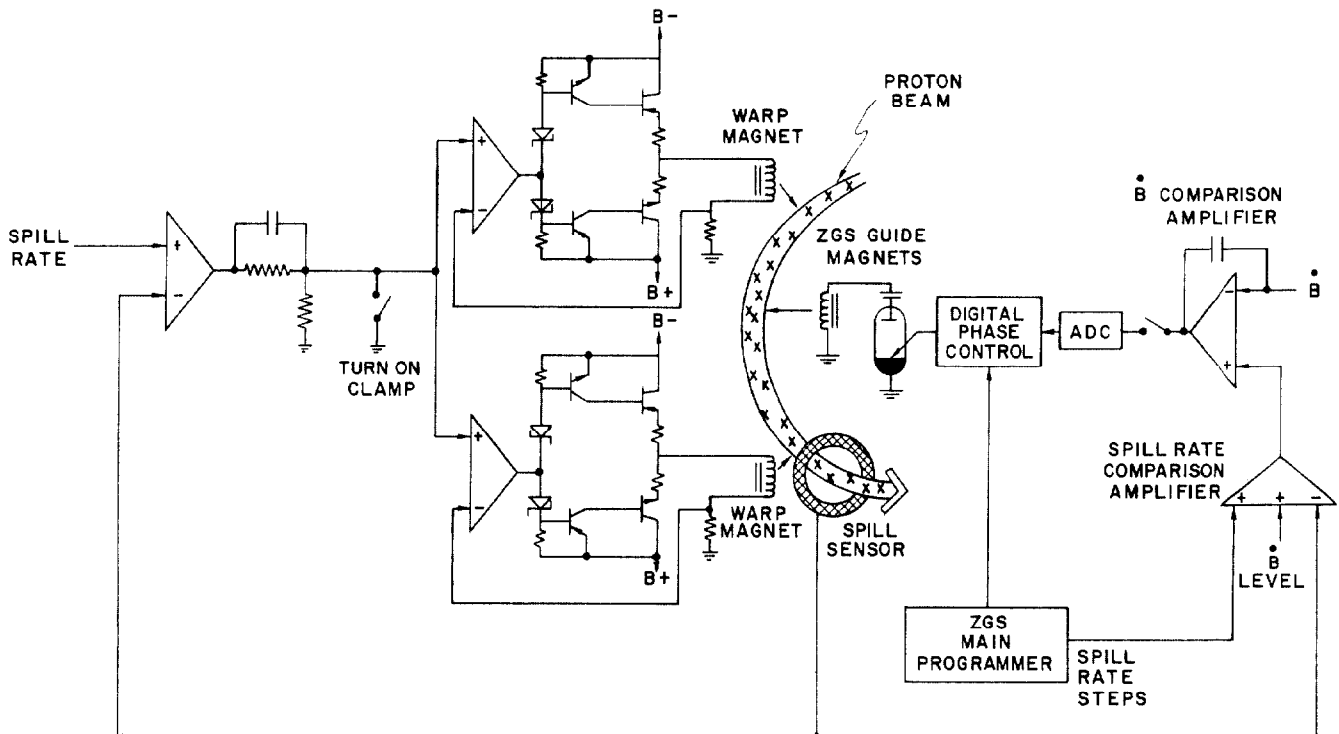


Fig. 1.  
Spill Feedback Control System

appears about 10 ms after the RF system is turned off. The magnetic ripple is always present in varying degrees. It can be shown that at 600 Hz, 0.0001% uncorrected main guide field ripple will cause 100% intensity modulation. It is difficult, if not impossible, to reduce ripple sufficiently; therefore, a feedback system (Fig. 1) is used to monitor the extracted beam and provide fast correcting fields to compensate for the structure caused by the ripple.

Referring to Fig. 1, the difference between the spill sensor signal and the spill rate command causes the main guide magnets to move the beam into the unstable fixed points of the  $\nu_x = 2/3$  resonance. This action sets the low frequency spill rate. A similar difference signal is sent to two 3 kW complementary symmetry transistor amplifiers. These amplifiers drive the two small spill control magnets which are referred to as orbit "warp" magnets because they provide small orbit deformations (warps) in the straight section where the resonance extraction sextupoles are located. The main guide magnets control the rate of spill between dc and 30 Hz and the warp magnets control the rate between 30 Hz and 10 kHz.

These warp magnets are small laminated C magnets. The transistor amplifiers driving these magnets can produce an  $\int B \cdot dl$  of only about  $\pm 160$  G ft, but this is enough to provide a compensating movement of  $\pm 0.1$  in. One gauss of guide field ripple causes a motion of 0.08 inches.

#### Operating Experience

The initial trials with this system were very promising, but it was soon learned from the users that the beam was 100% modulated about 800 Hz. Small fast argon filled ion chambers with improved electronics were constructed. Using these as spill sensors in the feedback loop resulted in 100% modulation of the beam at 3 kHz as shown in Fig. 2.

A careful analysis indicated that the feedback loop had some sort of dead zone in it. This could result from some nonlinearity around zero within the system electronics. None was found. Increasing the frequency response of the system by changing warp magnet inductance and damping parameters increased the structure frequency to 6 kHz, but the spill was still 100% modulated.

Of course, a time delay or spatial nonlinearity in the resonant extraction process itself could be the nonlinear element in the system. While computer

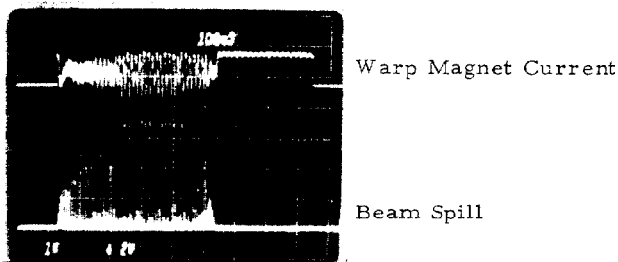


Fig. 2.  
Beam Spill Without Scrambling

studies indicated no nonlinearity in the extraction process, the results described below clearly point to its existence.

The nonlinearity in the extraction process was eliminated by two techniques. The first used the radial damper magnet and its power amplifier to magnetically "scramble" the beam. This is a picture frame ferrite magnet which can produce a dipole field of 0.52 G ft at frequencies as high as 1MHz. Decreased intensity modulation of the extracted beam was achieved by "scrambling" the beam with this magnet running at  $569 \pm 1$  kHz or  $589 \pm 1$  kHz. The  $(1-\nu_x)$  frequency of the  $\nu_x = 2/3$  extraction process is 579 kHz. No other  $\nu_x$  parameter of the spill control loop was changed. A comparison of Figs. 2 and 3 shows the improvement. Extracted particle momenta has varied from 2.0 to 12.3 GeV/c. Beam densities change by a factor of 100 during polarized proton operation, but the least kHz structure always results when the magnetic scrambler is run from 0.8% to 1.5% off of the  $(1-2/3)$  frequency for a given momentum. The corrective band width for any one beam condition is always less than  $\pm 0.2\%$ . It was suspected that structure at the scrambling frequency might exist. This has been noted by some users, but is usually not objectionable.

A second technique was developed using the ZGS radio frequency system. In this technique, the RF voltage is reduced to zero for about 15 ms, then turned back on at a specific nonsynchronous frequency. Nonsynchronous correcting frequencies can be found both above and below the synchronous frequencies. These correcting frequencies are found by tuning for the least structure. They are found from 0.3% to 0.6% away from the synchronous frequency. The RF corrections also exhibit a frequency selectivity, but are not as sharp as those of the magnetic mode. An optimum RF voltage amplitude is also found empirically, although no sharp peak is distinguishable. The best amplitude is usually about 20% of peak accelerating voltage. The use of RF scrambling also seems to reduce the 15% RF structure remaining after RF turn off. Comparison of Fig. 4 to Fig. 2 shows the improvement made by RF scrambling.

Both magnetic scrambling and RF scrambling display a saturation level. Driving the beam harder does not produce better spill structure, in fact it may get worse. However, when both techniques are used simultaneously, further improvement is obtained as can be seen by examination of Fig. 5.

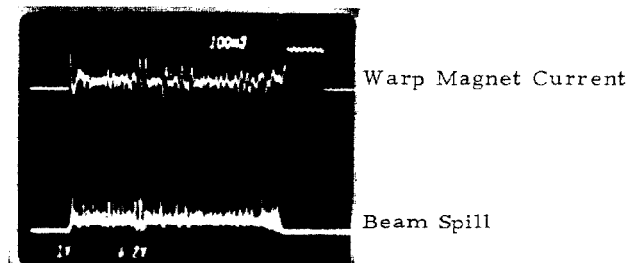


Fig. 3.  
Beam Spill With Magnetic Scrambling

## Theoretical Considerations

While no mathematical models have been developed to explain what is deficient in the extraction process and why these techniques correct these deficiencies, some thought has been given to why it works. It has been suggested that once a particle gets near the unstable fixed point its behavior is not well defined and small random perturbations might keep the particle in the machine for thousands of turns. The reasoning follows that a small nonrandom perturbation, such as radial motion created by magnetic scrambling, would prevent the particle from setting at the unstable fixed point.

During "RF scrambling" the beam energy spread is increased as the beam drifts with respect to the nonsynchronous RF buckets. Having a variety of energies provides a more continuous stream of particles, thus minimizing any spatial nonlinearities. However, if increased energy spread is the only determining factor, why does the improvement show frequency selectivity? Improvement by each technique reaches a saturation point, yet when both are applied simultaneously, further improvement results. This suggests that RF scrambling and damper scrambling do not operate through the same mechanism, so both explanations may be correct.

## Some Useful Apparatus

### Structure Index Monitor

Since the structure is minimized by tuning, some gauge of successful tuning is required. Fourier analysis of spill signals is the most obvious answer, but adequate sampling of an 800 ms spill takes excessive computer memory. Another structure monitor that is used at the ZGS has been previously described.<sup>4</sup> It analyses several frequency components individually for 50 ms. This is helpful in diagnosing where structure may be coming from, but is not very useful in trying to get the least intensity modulation over the whole flattop.

A scheme is used that the operators find helpful. In channel one, the spill signal is integrated. In channel two, a slow tracking peak detector is used on the spill signal. The output of the peak detector is then integrated, producing an integral of the upper enve-

lope of the spill signal. Both integrators are sampled by the computer after the spill. The computer divides two by one and displays the ratio. A number of 100 is a perfect dc spill. An index of 110 is routinely achieved which indicates about 20% modulation.

### Intensity (Q) Measurement of Unbunched Beam

Due to the large accelerating aperture, the ZGS has no toroid for measuring unbunched circulating beam intensity. Such a signal is required for establishing beam distribution during the extraction. Measurement of ions created by the circulating protons is used as a measure of debunched beam, but of course its calibration depends on the residual pressure near the collecting electrode. An induction electrode measurement of the intensity of bunched beam is the ZGS beam intensity standard. An electronic scheme has been devised to calibrate the ion Q system every pulse.

The ion Q signal is locked to the bunched Q signal with a closed loop system until just before the RF is turned off on flattop. The error signal in the loop that keeps the ion Q in dynamic calibration is sampled and held through the accelerator flattop. Thus, the ion Q system is calibrated with respect to bunched Q at full energy each cycle.

## References

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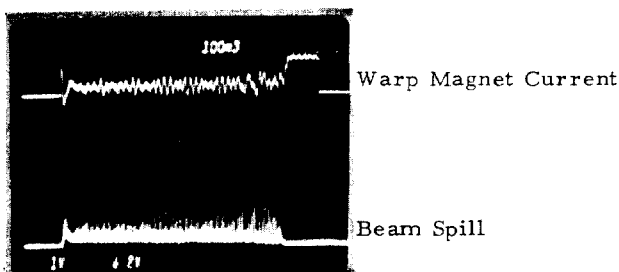


Fig. 4.  
Beam Spill With RF Scrambling

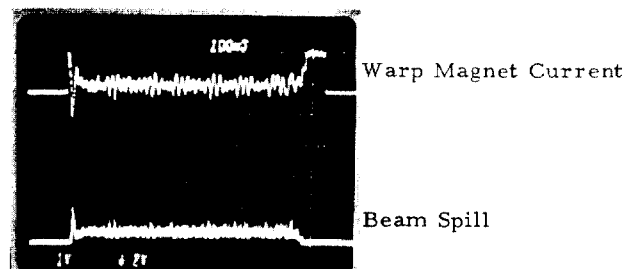


Fig. 5.  
Beam Spill With RF and Magnetic Scrambling