

RIPPLE FILTER SYSTEMS OF THE ZERO GRADIENT SYNCHROTRON AND MEANS FOR LONG, MAGNETICALLY CONTROLLED BEAM SPILLS*

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Summary

Ripple frequencies in the ring magnet guide field of the Zero Gradient Synchrotron (ZGS) range from less than 1 Hz to several kHz. Filter systems which reduce the ripple components to negligible magnitudes are described, as is the use of these systems for long, magnetically controlled beam spills. High frequency ripple is attenuated by an improved LCR filter. Low frequency ripple is reduced by a feedback loop from B to the rectifier phase control of the ring magnet power supply (RMPS). The attenuation of the mid-frequency components is accomplished with a feedback loop from B to a ripple bucking coil in each octant of the ZGS. Two modes of operation for magnetically controlled beam spills without RF structure are discussed. In one mode the feedback to the low frequency loop is a signal from a spilled beam monitor. In the second mode the spilled beam monitor drives both the low frequency and the mid-frequency loops.

Reduction of Ripple Flux in the ZGS Ring Magnet during Flattopping

During the first few years of operation, the device used for attenuating RMPS ripple was a critically-damped LCR filter that peaked at 48 Hz and attenuated higher frequencies by 6 dB/octave. This filter proved to be inadequate, however, since enough ripple remained in the guide field to affect the quality of the long, RF controlled beam spills.

To reduce ripple to negligible amounts, the passive filter was improved, and two active filters were added. The active filters are in use only during flattopping, while the passive filter is used throughout the ZGS cycle. Figure 1 is a block diagram showing these filter systems.

LCR Low Pass Filter

By adding a 1500 μF capacitor, C_1 , across the output of the original filter, the low pass filter shown in Fig. 1 was obtained. This boosts the attenuation of higher frequencies to 12 dB/octave, and the filter response now peaks at 67 Hz. Its component values are $R_1 = 2 \text{ m}\Omega$, $L_1 = 1.5 \text{ mH}$,

$C_1 = 1500 \mu\text{F}$, $C_2 = 7250 \mu\text{F}$, and $R_2 = 1 \Omega$. The value of C_1 was chosen such that the filter will not ring when the RMPS is pulsed.¹ The filter response to a step voltage is shown in Fig. 2. The filter transfer function is

$$\frac{e_o}{e_i} = \frac{1 + sT_2}{1 + sA + s^2B + s^3C} \quad (1)$$

where

$$\begin{aligned} A &= T_1 + T_2 + T_3, \\ B &= L_1(C_1 + C_2) + T_1T_2 \\ C &= L_1C_1T_2, \\ T_1 &= R_1C_1, \\ T_2 &= R_2C_2, \text{ and} \\ T_3 &= R_1C_2. \end{aligned}$$

The magnet load has a negligible effect on the filter performance.

Active Low Pass Ripple Filter

The RMPS has four groups of 12-phase rectifiers. During flattopping the magnet voltage, E_{dc} , is equal to the IR drop of the magnet coils and is controlled by adjusting the firing angle, α , of the rectifiers ($E_{dc} \approx K_1 \cos \alpha$). The ZGS programmer does this by setting the open loop phase control voltage, e_ϕ , appropriately ($\alpha \approx K_2 e_\phi$). After flattop is attained, a closed loop voltage, Δe_ϕ , is connected in series with the open loop phase control voltage.² For a 21.5 kG flattop, e_ϕ is about 100 V dc. This limits Δe_ϕ to -100 V, which causes full inversion ($\dot{B} \approx -16.4 \text{ kG/s}$), and +150 V, which causes full rectification ($\dot{B} \approx 19.8 \text{ kG/s}$).³ For low frequency ripple attenuation, much lower B values are required. Figure 3 illustrates the ripple attenuation vs. frequency of the active low pass filter.

Active Bandpass Ripple Filter

As shown in Fig. 3, ripple attenuation with the active low pass filter is appreciable only up to a

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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few Hz. So that this filter and the bandpass filter do not oppose one another, the bandpass of the latter was chosen to be 10 Hz to 2 kHz. The upper cutoff frequency was chosen for two reasons. At frequencies above 2 kHz, ripple flux levels are negligible due to the passive LCR filter, and the ring magnet impedance characteristics at frequencies around 10 kHz make stabilization extremely difficult for a wider bandpass system.⁴ The chart below gives typical ripple components taken during 19.8 kG flattops from the B coil of one of the eight ZGS octants.

Frequency (Hz)	Peak-to-Peak Ripple Flux (mG)
10	724.70
20	900.00
30	722.50
48	579.60
96	432.60
144	72.40
290	97.60
580	18.70
870	6.80
1160	4.30
1450	2.90
1740	1.50
2030	0.90
2320	0.27

A block diagram and a partial schematic diagram of the ripple reduction circuitry of the bandpass filter system are shown in Figs. 4 and 5 respectively. Because of small electrical differences, each octant of the ring magnet requires its own filter system. Ripple reduction with this system is accomplished by integrating a signal from the B shield and feeding it through a lead-lag compensating network and into a power amplifier. The load of the amplifier is a ripple bucking coil which is mounted close to the main magnet and the B coils. Prototype tests have yielded ripple reduction across the passband by a factor greater than 25. This reduces mid-frequency ripple fluxes in the octants to negligible levels.

To protect the power amplifier from over-voltages during rectify and invert, it is electrically disconnected from the ripple bucking coil at all times other than flattopping. A pulse from the ZGS programmer is used to turn on the bandpass filter system shortly after the beginning of flattop and to turn it off just before inversion (Figs. 4a and 4b). The system shown in Fig. 5a is normally turned on by simultaneously triggering SCRs 1 through 4 with a 100 kHz square wave and normally turned off by shutting off SCRs 3 and 4. During emergencies all four SCRs are

pulsed off. The method used to turn off these SCRs is shown in Fig. 5b. When SCR 5 is pulsed on, the voltage on the 125 μ F capacitor is applied to the inductor in series with the SCR to be turned off. This LC circuit will reverse bias the SCR long enough to insure turnoff. After the LC circuit oscillates for one-half cycle, the current tries to reverse, thereby turning off SCR 5 also. If the system is turned on during any time other than flattopping, it will automatically shut itself down. Depending upon the nature of the failure, the system is either automatically turned back on during the next flattop or shut down until it is manually reset. Overvoltage protection for the output transistors of the power amplifier is provided by diodes D1 through D4 (Fig. 5a). Diodes D6 and D7 protect the input against overvoltages during full rectification and inversion.

Uniform Beam Spill without RF Structure

The radius of curvature, r , for a charged particle of kinetic energy, T , moving through a magnetic flux density, B , is given by the following expression,

$$r = \frac{(T^2 + 2 TE_o)^{1/2}}{9.15 B} \quad (2)$$

where r is in feet, B is in kG, and E_o and T are in MeV. For protons, the rest energy, E_o , is 938 MeV, and the equation becomes

$$r = \frac{(T^2 + 1876 T)^{1/2}}{9.15 B}$$

Thus, radial beam movement by targeting can be accomplished by:

1. holding the magnetic guide field constant and varying the energy of the particles,
2. holding energy constant and varying the magnetic field, or
3. simultaneously varying both energy and magnetic field.

A particle's energy is varied by changing the RF. Targeting by changing the radius of the beam with RF is suitable for experiments where RF structure on the beam is irrelevant. For RF controlled beam spills, switch S_1 in Fig. 1 is in position 1, and all filter systems are used solely for ripple reduction. However, for many experiments it is desirable to eliminate RF structure. In these cases, magnetically controlled beam spills are used in either of the following two modes of operation.

Beams without Abrupt Changes in Density

Beams with a constant or a gradually changing density can be spilled uniformly by changing the ring magnet field by means of the RMPS. This method for beam spill is illustrated in Fig. 1 with switch S_1 in position 2. In this mode the active bandpass filter system is still used for ripple reduction with \dot{B} as its input. A signal from a beam spill monitor is the input to the active low pass filter system.

As a worst case example, a 3 in. circular beam of uniform density is to be spilled during a 21.5 kG flattop on an inner target. With a momentum compaction of 0.6, the ZGS requires a field change on the order of 18 G to move the beam 1.5 in. If this beam is to be spilled during a 200 ms flattop, an average \dot{B} of 90 G/s is required. However, to spill it uniformly, \dot{B} must be changed throughout the spill time as shown below.⁵

Spill time	0	0.5	2	5	10	200	ms
\dot{B} required	∞	750	390	200	158	67	G/s

The active low pass filter is limited to $-5.3 \text{ kG/s} < \dot{B} < 4.8 \text{ kG/s}$ at 21.5 kG flattops. However, the time delays inherent in the RMPS rectifiers ($\leq 1.63 \text{ ms}$) and the LCR filter ($\approx 3.7 \text{ ms}$) prevent one from having a uniform spill before approximately 5% of the beam has been spilled.

Beams with Abrupt Changes in Density

From the above it is apparent that the active low pass filter system cannot respond to fast changes in beam spills or abrupt changes in beam density. For this reason, the current capability of the power amplifier of the bandpass filter system is $\pm 100 \text{ A}$, which is much greater than is needed for ripple reduction. The increased current capability allows this system not only to be used for ripple reduction but also to be used in conjunction with the rectifier phase control system to magnetically control beam spills. This mode of operation is illustrated in Fig. 1 with switch S_1 in position 3. Signals from beam spill monitor and spill reference are inputs to both active filter systems. The fast response of the active bandpass filter system compensates for fast beam density changes and ripple.

Figure 6 shows the ampere/gauss ratio of the ripple bucking coil as a function of frequency.

For example, at 100 Hz the bandpass filter system has the capability of changing the magnetic guide field by 5 G. This field change moves the beam approximately 0.14 in.

Types of Uniform Beam Spills

Given the total charge, Q , in the ZGS during any one cycle, there are two methods for spilling a beam uniformly on a target.

1. With the spill selector switch, S_2 , in position 1 (Fig. 1), the beam charge in the ZGS is spilled uniformly over a predetermined time. The rate of the spill varies from pulse to pulse with the charge in the ZGS.
2. With the spill selector switch in position 2, the beam charge in the ZGS is spilled uniformly with a predetermined rate; the length of spill varies from pulse to pulse with the charge.

Moving the Beam between Targets

By varying the frequency, the RF system can change the radial position of the beam at an equivalent magnetic field rate of 20 to 25 kG/s. This rate is approximately equal to a beam movement of 2 in. per ms. The beam could also be moved by varying \dot{B} with the RMPS. The limits of theoretically obtainable \dot{B} values have already been given as -16.4 kG/s and 19.8 kG/s . With these values and a 21.5 kG flattop, the beam is moved 13 in. from an inner to an outer target in 9.5 ms and from an outer to an inner target in 7.8 ms. The feedback loop response time of approximately 4.5 ms must be added to these times. Thus, it is theoretically possible to use only the RMPS to position the beam during ZGS experiments, including multiple targeting experiments. However, fast changes in rectifier output voltage produce instantaneous load changes and transients. Load changes cause twists in the motor-generator set shaft and possibly excite shaft resonances. The transients caused by charging the filter capacitors may, at high magnet currents, cause arc faults. For the above reasons, the RF system is used to move the beam onto a target.

Figure 7 illustrates possible combinations of short, RF controlled spills followed by a long, magnetically controlled spill without RF. The RF system positions the beam for fast spills on the front porch and at the beginning of flattop. After the RF system has moved the beam onto the slow spill target, the RF system is shut off, and either of the two magnetically controlled modes of operation described above controls beam spill.

References

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5. W. F. Praeg, "Reduction of Ripple Flux During Flattopping and Feedback Loop to Ripple Bucking Coils for Uniform Beam Spills," Argonne National Laboratory, letter to L. C. Teng (April 20, 1965).

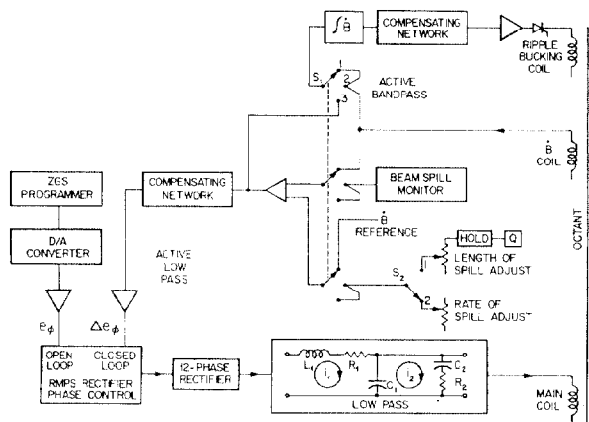


Fig. 1 - Block diagram of the ZGS filter systems

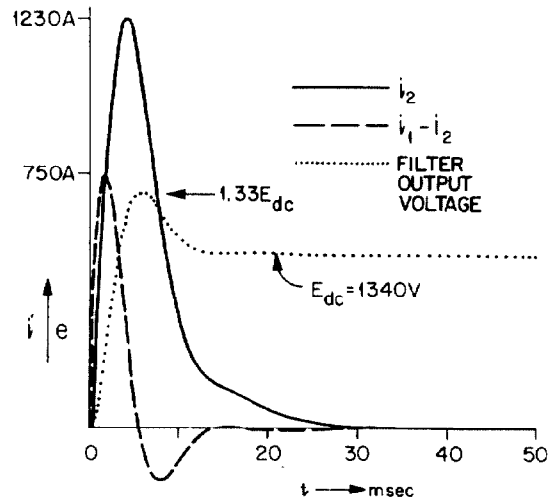


Fig. 2 - Low pass filter response to a step voltage

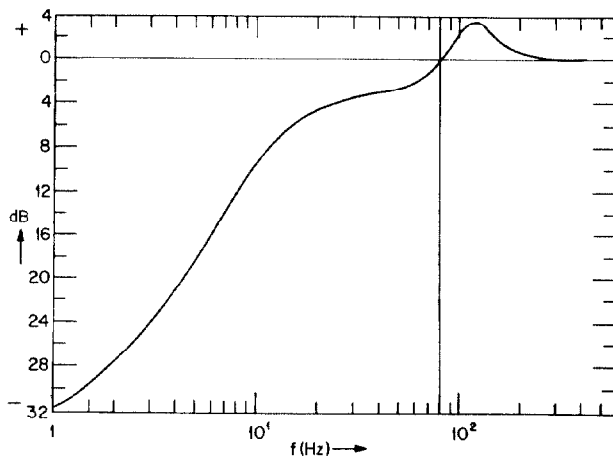


Fig. 3 - Ripple attenuation versus frequency of the active low pass filter system

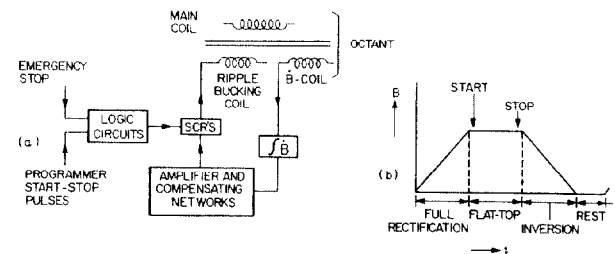


Fig. 4 - Block diagram of the active bandpass filter system

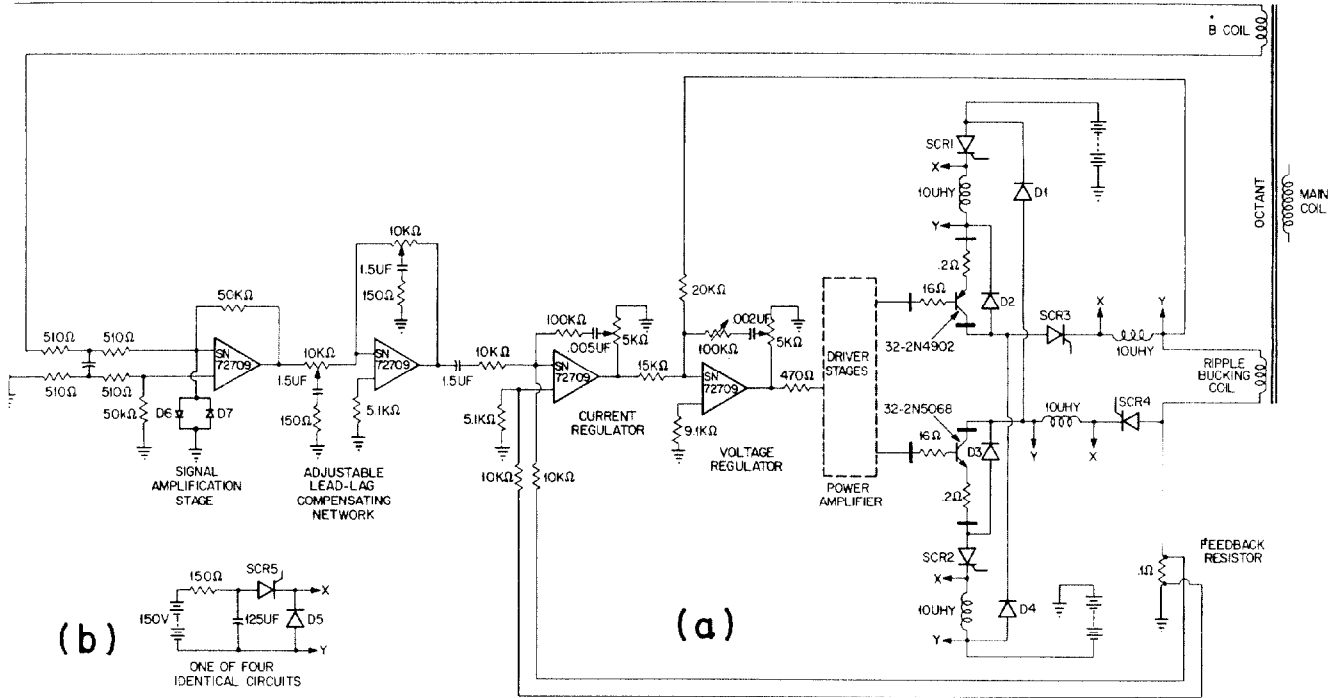


Fig. 5 - Partial schematic diagram of the active bandpass filter system

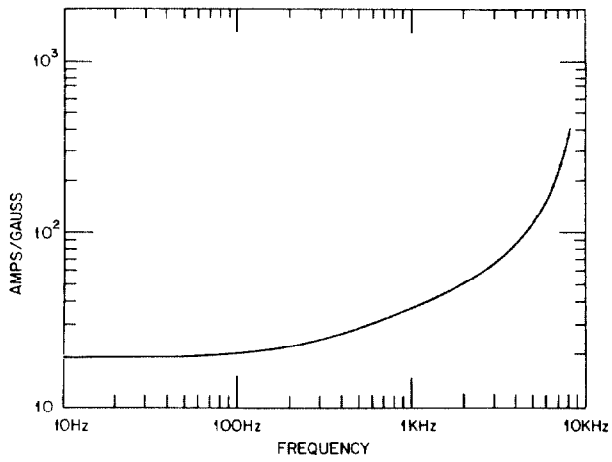


Fig. 6 - Ampere/gauss ratio of a ripple bucking coil

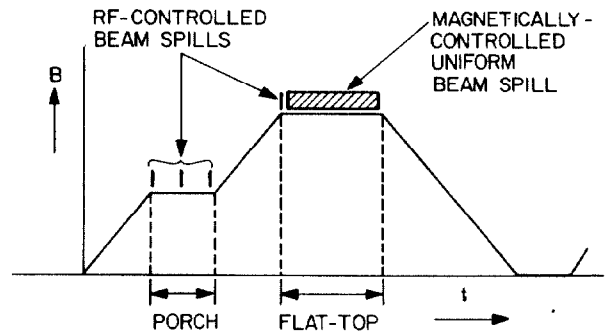


Fig. 7 - RF and magnetically controlled beam spills