The AGS New Fast Extracted Beam System Orbit Bump Pulser*

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Abstract

The AGS New Fast Extracted Beam System (New FEB) is designed for RHIC injection and the g-2 experiment, performing single bunch multiple extraction at the prf of 20 to 100 Hz up to 12 times per AGS cycle. Capacitor-discharge pulsers are required to produce local orbit bumps at the fast kicker and ejector magnet locations. These pulsers have to deliver half-sine current pulses at 1 KA peak with a base width of 5 msec. The discharge voltage will require approximately 800V with a $\pm 0.1\%$ accuracy. Direct charging will require a charger too costly and difficult to build because of the high prf. An alternative charging system is being developed to take advantage of the 1.5 sec idle time between each group of pulses. The charger power supply ratings and regulation requirements are thus greatly reduced. The system analysis and results from a prototype will be presented.

I. INTRODUCTION

In previous fast extraction systems of the AGS, either a single bunch was kicked out per cycle, or all 12 bunches were extracted in one revolution. In the AGS's New Fast Extracted Beam system (NewFEB) the requirements are for single bunch multiple extraction which normally extracts 3 bunches in a row, but with a capability of up to 12 consecutive bunch extractions. This would normally not present a severe problem but for the fact that it has to be accomplished at a pulse repetition frequency of 50 Hz. This requirement is set by both major users, the g-2 muon anomalous magnetic moment measurement[1],which is statistics dominated and hence requires very high average beam intensity, and RHIC injection[2]which should be accomplished as quickly as possible to prevent beam quality deterioration in its beam stacking mode. DC supplies either cause beam orbit problems in the AGS or equipment heating problems that are difficult or unreliable to overcome. Due to the amount of stored energy in the orbit deformation bumps and the ejection septum, large capacitor banks must be used. To charge these banks in less than 15 msec, the charging power supplies would be complex and expensive to construct. A quick approximation shows that a 800V/300A/0.1% charging power supply is needed for the task. Charging supplies of this category can only be found in high frequency switching technology. The charging power supply also suffers from low efficiency because between the 12th pulse and the beginning of the next AGS cycle, there is a 1.5 sec idle time which the charging supply is doing nothing. This is why we looked for a new, more reasonable method to recharge the capacitors.

II. SYSTEM PARAMETERS

Each pulser has 4 AGS Main Magnet Back-Leg Windings connected in series as the load. The system parameters are summarized as the following.[3]

Beam deflection	:	2 mrad per pair of magnets
Peak Field	:	500 Gauss
Peak Current	:	1000 A
Pulse Rep. Rate	:	50 Hz, 1-12 times/AGS cycle
Wave Form	:	Half-sine with 5 msec basewidth
Inductance	:	1.2 mHy
Discharge Voltage	:	750 V
Discharge Cap.	:	2110 uF
Discharge energy	:	593 J
Reproducibility	:	± 0.1 %
No. required	:	4 pulsers

III. DESIGN AND ANALYSIS

A. Design and Circuit Realization

Our design shown in fig. III.1 has many advantages. The charging supply does not directly charge up the discharge capacitor C2. Instead, it supplies current into a large capacitor bank C1 whose capacitance is 1 to 2 orders larger than C2. A large C1 is necessary to prevent excessive voltage drop in each successive charging of C2. C2 is charged up very accurately through the switch G1 which is controlled by the feedback loop. When C2 voltage reaches the reference level, G1 opens and stops charging. C1 is replenished to 850V, which is 100V higher than the discharge voltage requirement of C2, from the charging power supply during the 1.5 secs idle time and is ready for the next AGS cycle. The first immediate consequence is that the power supply current rating is greatly reduced due to the long charging time. Secondly, the burden of accuracy is shifted from the charging supply to the feedback loop and the switch G1. An ordinary 3 phase off-the-shelf SCR power supply will satisfy the design requirement.

All circuit elements are readily achievable. Fig. III.2 shows the system implementation in component level. G1 has to withstand at least twice the supply voltage (2 x 850 = 1700 V) due to fly-back voltage of C2. Transistors are

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ruled out because the voltage is too high. A GTO appears to be a good choice in implementing the switch G1 for its excellent voltage blocking, fast operating, and current interrupting capabilities. An asymmetrical GTO will suffice because the voltage of C1 is always higher than that of C2. Further, the gate drives of GTOs are commercially available. Although C2 have to be quality discharge capacitors due to voltage reversal, C1 can be implemented with inexpensive and high capacitance-per-volume aluminum electrolytic capacitors. These aluminum can capacitors have a maximum voltage rating of 450V DC; therefore, two stacks in series are needed in our application. Alternatively, resonant LC charging can be used provided the accuracy requirement is not too stringent.

B. Analysis

The objective of this section is to calculate the charger power supply rating requirement and to discuss the source of pulse to pulse error .

1. Power Supply Rating

The power supply rating is calculated using the law of conservation of charge. In each charging process, the charge loss from C1 must equal to the charge gain by C2. Therefore,

$$C1\,\Delta V1 = C2\,\Delta V2 \tag{1}$$

where $\Delta V1$ = Voltage drop of C1 per recharge
$\Delta V2$ = Voltage gain by C2 per recharge
Assuming the fly-back choke is able to recover 50% of the initial C2 voltage, $\Delta V2 = (0.5)(750) = 375$ V. Since C1 is chosen to be 100 times larger than C2, $\Delta V1$ can be determined. The total voltage drop of C1 for 12 pulses is 45 volts. C1 has an initial overhead of 100V more than the discharge voltage of C2, therefore the 45 volts drop is well covered. C1 is recharged during the 1.5 sec idle time. The current rating can be calculated.

$$12(C1)(\Delta V1)/1.5 = 6.33amp \tag{2}$$

The minimum charging power supply rating is 850V and 6.33A.

2. Source of Pulse to Pulse error

The source of pulse to pulse error comes from the GTO turn-off delay which is approximately 25 us. Fig. III.3 shows the RC charging current wave form through the GTO. The initial charging current at the GTO turn-on for each pulse is successively lower for each extraction pulse, but the charging time is longer. C2 is overcharged for 25us at a different current interrupting level. The difference in overcharge constitutes the pulse to pulse error.

The current interrupting level can be obtained as follows:

$$\begin{aligned} Icut_n &= (V_n - 750)/R \\ V_n &= 850 - (n)(\Delta V1) \end{aligned} \tag{3}$$

where n = 1..12
$Icut_n$ = current interrupting level at nth recharge
V_n = voltage of C1 at the end of nth recharge.
The largest pulse to pulse discharge voltage variation is

$$Verr = (Icut_1 - Icut_{12})(25)(10^{-6})/C_2 \tag{4}$$

and the percentage error is

$$\%err = (Verr/750)(100\%) \tag{5}$$

We also want to check the charging time t_n for each pulse to make sure that it does not exceed the available time frame of 10ms (Recall that there is a 20ms period between each pulse. 5 ms is used for discharge and 5 ms is used for energy recycling). Assuming C1 >> C2, the following charge relationship can be approximated.

$$\int_o^{t_n} \frac{(V_{n-1} - V2)}{R} e^{-\frac{t}{RC2}} dt = (C2)(\Delta V2) \tag{6}$$

where V2 = voltage recovered on C2.
Solving for t_n,

$$t_n = -RC_1 \ln(1 - \Delta V2/(V_{n-1} - V2)) \tag{7}$$

We conveniently chose R = 1 ohm and again assume 50% C2 voltage recovery. The calculated results are %err =0.07% and t_{12}= 4.2 msec. Both values are certainly within the specification of the system requirement.

IV. PROTOTYPE RESULTS

A scaled down prototype was built to confirm the capability of the system. In reference to fig.III.2,

C1	=	50,000	uf
C2	=	2,000	uf
Lo	=	1	mHy
Lf	=	1.8	mHy
R	=	1	ohm

C1 was charged up to about 210 V initially and the reference for the C2 discharge voltage was set to 150 V. Six pulses were fired at the rep. rate of 20 msec per AGS cycle. The peak current was measured to be 200 A. The current was measured at point A in fig.III.2. Fig.IV.1 shows the voltage(upper trace, 50V/div) and current(lower trace, 100A/div) of the discharge bank C2 for the first 2 pulses. The positive half-sine current pulse is the discharge current going to the load. The negative half-sine current recycles the energy back to C2 and recovers 73% of the discharge voltage. The negative trapezoidal current charges C2 from 110 V to the target 150 V.

The discharge voltage of C2 was measured using a triggered 16-bit digital voltmeter over 10 AGS cycles. The deviation of all the discharge voltages falls within ±0.1%. To achieve ±0.1% for 12 pulses, C1 will have to be larger. C1 is only 25 times larger than C2 in the prototype.

V. Conclusion

Both our analysis and prototype have demonstrated encouraging results. Our design greatly reduced the current rating of the charger. The control and accuracy of recharge is shifted from the power supply to the feedback control loop which can be modified easily for different applications. We have planned modifications to the reference and the feedback control to achieve pulse to pulse modulation operating mode.

Figure Captions

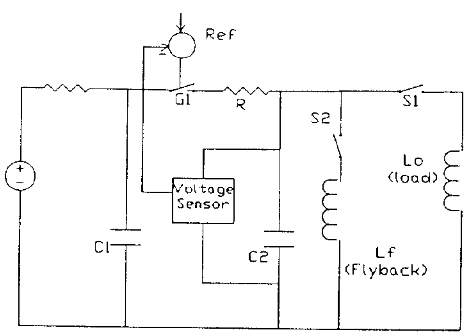

Fig. III.1 Design Configuration

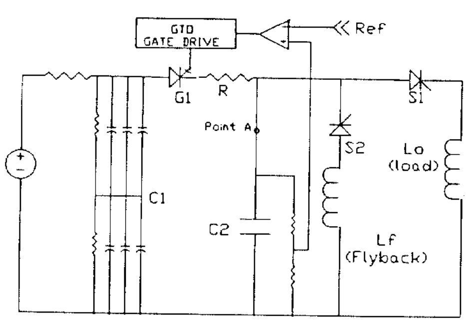

Fig. III.2 System Implementation

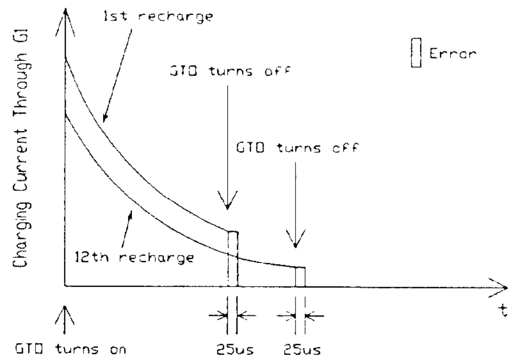

Fig. III.3 Source of Recharge Error

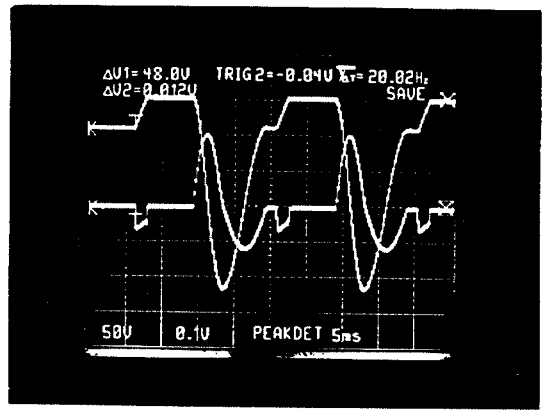

Fig IV.1 Discharge Voltage and Current
Measured at Point A in Fig. III.2
(Upper Trace 50V/div)
(Lower Trace 100A/div)
(Time Base 5ms/div)

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References

[1] Experiment 821, A New Precision Measurement of the Muon g-2 Value at the Level of 0.35 ppm.

[2] M. Tanaka and Y.Y. Lee, "The AGS New Fast Extraction System for the g-2 Experiment and RHIC Injection", Proc. 1991 PAC, San Francisco, Calif.

[3] M. Tanaka, private conversation.