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PULSED POWER SUPPLY SYSTEM FOR THE "FAST" QUADRUPOLES IN THE AGS*

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Summary

In the acceleration of polarized protons in the AGS, a number of depolarizing resonances will be encountered.[1] Depolarization due to the so-called intrinsic resonances will be minimized by crossing each resonance in less than one beam revolution period (~ 2 μs). This will be accomplished with a set of twelve "fast" tune-shifting quadrupoles distributed symmetrically around the ring.

During a typical acceleration cycle, the fast quads will be energized with a burst of alternating polarity, fast rise/slow fall triangular current pulses. The amplitude of these pulses will vary from 160 A to about 2700 A peak.

This paper describes the development of the pulsed power supply for the fast quads, the construction of a prototype modulator and some of the initial test results obtained with the prototype.

Introduction

At the present time there is a program underway at Brookhaven to accelerate polarized protons in the AGS. Acceleration up to about 26 GeV will require the crossing of a number of intrinsic and imperfection depolarizing resonances. Beam depolarization due to the intrinsic resonances will be minimized by crossing or "jumping" each resonance in less than one beam revolution period. Resonance jumping will be accomplished with a set of so-called "fast" quadrupoles which will shift the vertical tune of the machine either up or down from the nominal value depending on the particular resonance.

The fast quadrupoles will be evenly distributed around the machine circumference, i.e., one magnet per superperiod. These magnets will have high frequency ferrite poles and ceramic vacuum chambers. The inner surface of each chamber will be coated with a thin metallic layer to prevent charge build-up, however, the coating will be sufficiently thin to be essentially transparent to the pulsed field. The inductance of each magnet will be approximately 6 μH.

During a typical acceleration cycle, these quads will be energized with a burst of triangular alternating in polarity pulses. The amplitude of the excitation pulses will vary from 160 A to about 2700 A peak. All fast quadrupoles will be pulsed simultaneously so that the total required tune shift takes place within a 2 μs period. The fall-time of the pulses will vary from 1.0 to 3.5 ms depending on the resonance. For polarized protons the AGS will operate at a nominal rate of one cycle every 2.4 secs.

Due to the distributed nature of the system and high required di/dt, each quadrupole will be powered by its own modulator. With limited space in the machine tunnel, the modulators will be located in separate buildings outside the tunnel approximately 100 - 150 ft. from the magnets and will power the magnets via coaxial pulse transmission cables. This arrangement should improve both the reliability and serviceability of the ps equipment.

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Magnet Excitation Requirements

As already mentioned in the previous section, during each acceleration cycle the fast quadrupoles will be energized with a burst of triangular current excitation pulses. Each pulse will have a fast rise ($t_r \leq 2.0$ μs) and a slow fall as shown in Fig. 1. The parameters of these pulses, i.e., peak amplitude, I_m, base width τ_d, and the time of resonance crossing, t_x, are given in Table I. Since the pulses within the burst alternate in polarity, each pulse has two labels- one with and the other without regard to polarity.

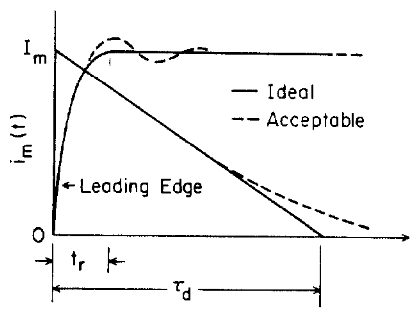

Fig. 1. Detail of a typical magnet excitation pulse

Table I

Pulse No.	E(Gev)	t_x(ms)	I_m(A)	τ_d(ms)
1, (1P)	1.70	69	35	1.0
2, (1N)	4.58	142	− 451	3.5
3, (2P)	7.98	178	197	1.0
4, (2N)	10.85	226	−1071	3.0
5, (3P)	14.26	296	1409	3.5
6, (3N)	17.13	358	− 592	1.0
7, (4P)	20.53	431	1014	1.2
8, (4N)	23.41	504	−2252	3.5

PS System Design

With a general description of the system given in the first section and the excitation requirements defined in Table I, the design goals and constraints for the power supply can be summarized as follows:

PS System — Design Goals and Constraints

1. Generate bursts of triangular current pulses simultaneously in 12 quadrupoles	8 pulses/burst Pulse sep. - 36 ms
2. Bipolar Output	
3. Wide Range of Pulse Amplitudes	160A - 2700A
4. Fast Rise/Slow Fall Pulses	$t_r = 2.0$ μs $t_f = 3.5$ ms
5. Pulse Repetition Rate	1 burst/2.4 s $2 \cdot 10^6$ pulses/week
6. Individual Pulse Height Adjustment	±20%
7. Pulse Height Stability	± 1%
8. Long Pulse Life	$> 10^8$ pulses
9. Long MTBF	$> 10^7$ pulses
10. Minimum Cost	

From the above requirements it is immediately possible to draw certain important conclusions about the power supply. First, due to the high di/dt and the 6 μH magnet inductance, the peak power supply output voltage will have to be in the order of 15 kV. Next, the long fall time coupled with small turn-on jitter and high voltage requirements can only be met at the present time with composite switches made up by paralleling thyratrons and ignitrons.

Modulator Design

To gain some insight into the design problem at hand, consider the problem of generating a single pulse with the simple circuit of Fig. 2. An examination of circuit parameters shows that in this case the simplest approach is uneconomical. In the above figure, where the parameters have been adjusted for the 4N pulse, both the energy discharge capacitor C and the high voltage charging power supply are expensive. An extension of the circuit to a bipolar n-pulse circuit, n = 2, 3, ..., would be prohibitively expensive in view of the fact that twelve such systems are required to power the quads.

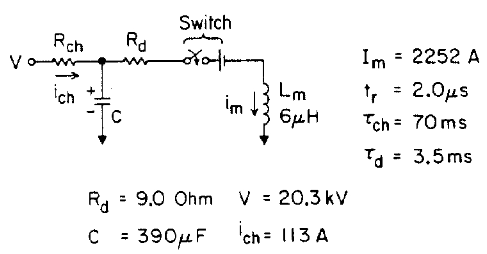

Fig. 2. A simple single-pulse circuit

After considering several alternate designs, the circuit of Fig. 3 has been chosen. In this circuit the pulse is generated in two sections - the leading edge is established by C_H and L_m, while the falling edge is determined by C_L and R_d. Compared with the circuit of Fig. 2, the high voltage required to develop the peak current is reduced by almost a factor of two and the size of C_H to a fraction of a microfarad. The "low" voltage capacitor C_L is rather large but its operating voltage is in the order of 1 kV. In fact, the magnitude of V_L is determined by the critical anode voltage of switch S_2.

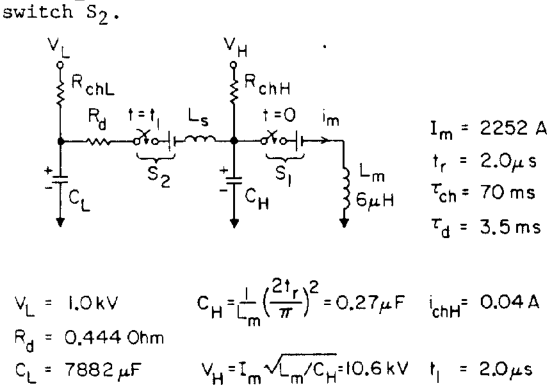

Fig. 3. A two-section single pulse circuit

An extension of the circuit of Fig. 3 to a bipolar n-pulse circuit, n = 2, 3, ..., can be readily made as shown in Fig. 4. The augmented circuit employs a single bipolar high voltage section and n unipolar "low" voltage circuits (P_1, N_1, P_2, ...). Capacitor C_H in the output section is charged either positively or negatively with a bipolar high voltage power supply V_H and discharged into the load with one of the unipolar output switches, So^+ or So^-, depending on the polarity of the pulse. The low voltage circuits are charged with separate power supplies (V_{P1}, V_{N1}, etc.). This scheme permits slow charging of the low voltage capacitors C_L which greatly reduces the size of the charging power supplies. It also permits parallel charging of low voltage circuits in a number of modulators with a resulting simplification of the system pulse amplitude control.

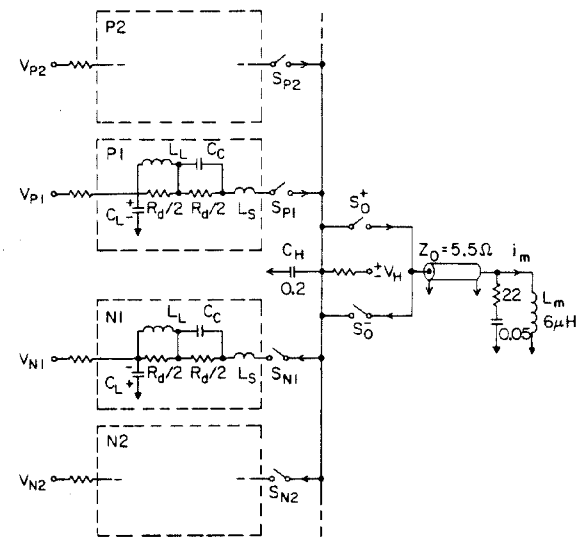

Fig. 4. The bipolar n-pulse modulator circuit

In each of the low voltage circuits of Fig. 4 there are two additional elements, namely L_L and C_c, each connected across one-half of the series resistor R_d. These elements have been omitted earlier for the sake of simplification. The effect of L_L is to linearize the slope of the trailing edge of the pulse. Capacitor C_c compensates for the voltage drop across S_1 and S_2 as well as for the effect of the stray inductance L_s. The main advantage of L_L is in that it reduces the size of C_L for a given initial slope. An additional advantage is that it reduces the amount of charge transferred per pulse which should help to extend the life of the switches.

Simulation

The circuit of Fig. 4 with 100 ft. of output cable has been simulated on a digital computer. Computed pulse No. 4N is shown in Fig. 5. For comparison, a pulse with the same initial slope but an exponential decay is also shown in the figure.

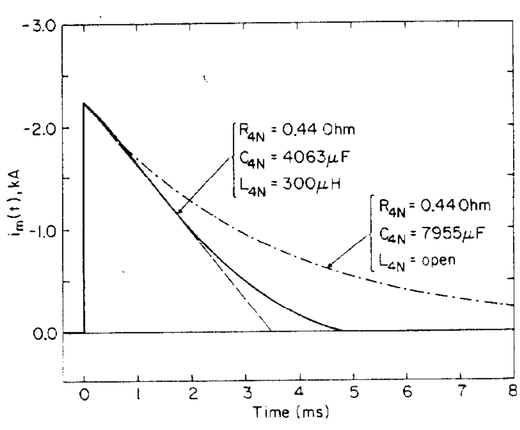

Fig. 5. Computed 4N pulse in the circuit of Fig. 4

The effect of stray inductance in the low voltage circuit on the shape of the front end of the output pulse has been computed and is shown in Fig. 6. From these results it is clear that in order to preserve a reasonable shape of the 4N pulse, the value of L_s must be kept below approximately 0.5 μH. In the case of the other circuits, where resistance R_d is higher, larger values of L_s may be tolerated.

In Fig. 4, the RC circuit at the end of the output cable serves as a termination for the leading edge of the pulse only. With the values of elements indicated, the amplitude of cable reflections which appear as a ripple on the front edge of the pulse is reduced to an acceptable level (see Fig. 6).

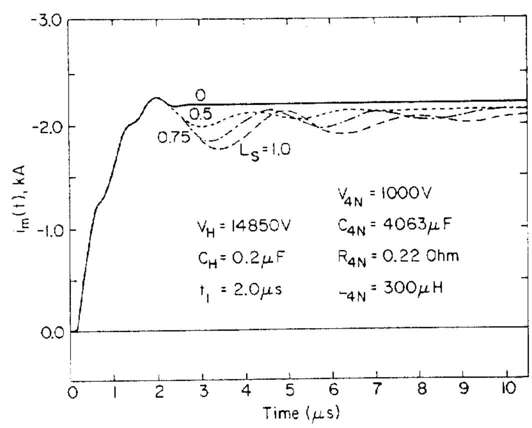

Fig. 6. The effect of stray inductance L_s on the front end of the pulse in Fig. 5.

System Configuration

The fast quad pulsed power supply system will consist of twelve modulators, one bipolar 20 kV and eight monopolar 1 kV charging power supplies. The modulators will be housed in separate equipment buildings outside of the machine tunnel and will power the quadrupoles in the ring via coaxial transmission cables. All of the charging power supplies will be located in one of the buildings and will be connected to the modulators with long charging cables placed around the ring.

Each modulator will be connected to the charging cables with a set of high voltage contactors. The modulators will be equipped with hard wired interlocks and control circuits which will automatically disconnect the equipment from the charging cables in case of malfunction.

The entire ps system will be controlled with a distributed computer network. Triggers for the system will be derived from a common source controlled by the computer.

Development Prototype

A development prototype of the modulator with four of the eight low voltage circuits has been constructed and tested. In the prototype, the switches are composed of EEV-1591 glass thyratrons and GE GL-37207 ignitrons. The above thyratrons are an improved version of the EEV-1538 which have been used with good success at Livermore. A number of composite switches made up of the same tubes have been tested by EEV at 3 kA peak and 3.5 ms base width. A total of about 10^7 pulses have been accumulated on each tube with only a few prefires or misfires.

The initial test results obtained using a short output cable show good agreement with calculations. A magnet pulse generated by one of the circuits with V_H = 6 kV and V_L = 1 kV is shown in Fig. 7. The leading edge of the pulse photographed on an expanded scale is also shown in the above figure. As can be seen, perturbation on the top of the pulse following the 2.0 μs rise period where the low voltage section of the circuit is switched in is about ±10%.

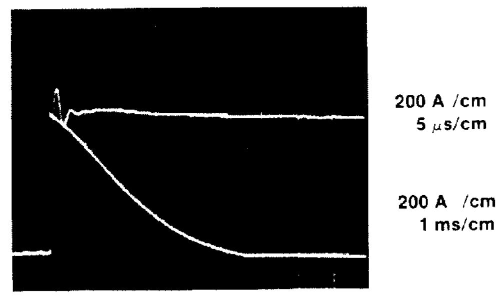

Fig. 7. Magnet current pulse generated by the prototype

Commutation of the current from the thyratron to the ignitron in one of the output tube pairs at 800 A peak is shown in Fig. 8. The broad leading edge of the ignitron current pulse is due to the ignitron turn-on jitter. As can be seen this effect is automatically compensated for by the thyratron so that the overall output pulse is stable.

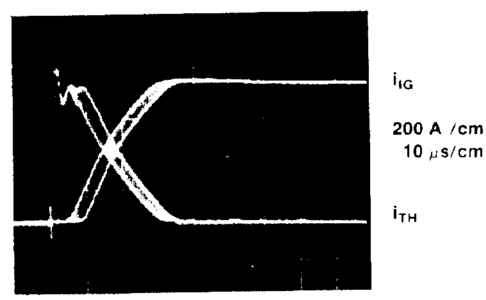

Fig. 8. Commutation of current from the thyratron to the ignitron in one of the output tube pairs

Acknowledgments

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References

1. E. D. Courant and R. D. Ruth, BNL Report No. 51270, September 1980.
2. R. F. Lambiase, AGS PP Tech Note No. 16, July 1982.