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THE 'FAST' QUADRUPOLE PULSED POWER SUPPLY IN THE AGS

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Abstact

As part of the Polarized Proton Project at the AGS, a pulsed power supply system has been developed to energize a set of twelve "fast" quadrupoles which are symmetrically distributed around the 1/2-mile circumference of the machine. During a typical acceleration cycle, which is normally repeated every 2.4 s, these magnets are energized with bursts of triangular current pulses. The rise-time of each pulse is less than 2 μs and the width at the base varies from 1 to 3.5 ms depending on the pulse. Within a burst, pulses alternate in polarity and vary in amplitude from 160 A to 2700 A peak. Pulse separation is on the order of 40 ms.

Due to the distributed nature of the load and high di/dt, each magnet is powered by a separate modulator. Magnets are driven via coaxial pulse transmission cables up to 200 ft long. In the modulators, the high power pulses are switched with thyratron/ignitron switch pairs. All modulators are charged in parallel with a common system of programmable high voltage power supplies. The overall system is controlled with a distributed network of microcomputers. This paper describes the development, construction and initial performance of the pulsed power supply system.

Introduction

Presently, there is a program underway at Brookhaven to accelerate polarized protons in the AGS up to 26 GeV. During acceleration, more than fifty depolarizing resonances of two types (imperfection and intrinsic) must be crossed. To minimize beam depolarization while crossing the eight intrinsic resonances, a series of fast-rise/slow fall vertical tune shifts is introduced by pulsing a set of so-called "fast" quadrupole magnets in the ring. Thus during each acceleration period, the fast quads are energized with a burst of eight triangular current pulses which alternate in polarity and vary in amplitude from 160 A to about 2700 A peak. All magnets are pulsed simultaneously so that the total required tune shift takes place within one beam revolution period or approximately 2 μs. For polarized protons, the AGS operates at a nominal rate of one cycle every 2.4 sec.

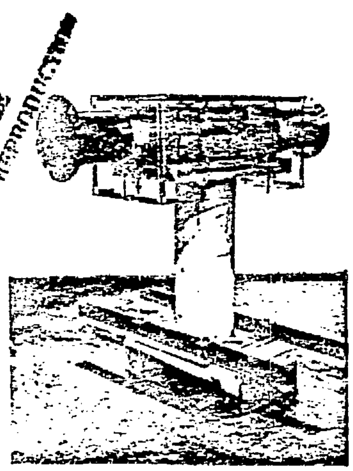

Fig. 1 A fast quadrupole magnet

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The fast quads utilize high frequency ferrite cores and ceramic vacuum chambers. The inside surfaces of the vacuum chambers are coated with an 8000 Å thick Al film to prevent charge build-up in the ceramic and to maintain a low rf impedance. The layer is thin enough, however, to be transparent to the pulsed field. The inductance of a fast quad, shown in Fig. 1, is approximately 6 μH.

Due to the distributed nature of the system and high required di/dt, each quadrupole is powered by its own modulator. With limited space in the machine tunnel, modulators have been installed in small buildings outside and energize the magnets via coaxial pulse transmission cables. This realization also provides an easy access to the equipment for test or maintenance purposes. A prototype of the system has been described in an earlier paper (1).

Pulse Specifications

Parameters of magnet excitation pulses within a burst, such as peak amplitude, I_m, base width, τ_d, and time of resonance crossing, t_x, are given in Table I. The required pulse waveform is shown in Fig. 2 where the rise-time $t_r = 2$ μs. In Table I, pulses have been labeled sequentially with and without regard to polarity (i.e., P1 is the first positive pulse, etc.)

Table I

Pulse No.	E(Gev/c)	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

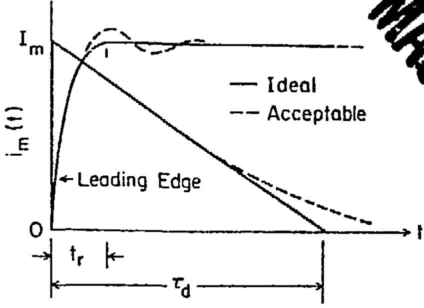


Fig. 2 Required pulse waveform

System Design Considerations

The design goals and constraints for the overall system are summarized in Table II.

Table II

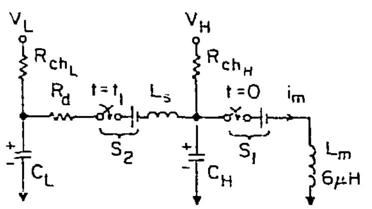
PS System — Design Goals and Constraints

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	$t_r = 2.0\ \mu s$ $t_f = 3.5$ 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 Table II it is clear that for the given magnet inductance and required di/dt the peak driving voltage must be of the order of 15 kV. With the present state of technology, the combined requirement of a long fall-time, small turn-on jitter, high output voltage and long pulse life can only be met with composite switches made up of thyratrons and ignitrons.

Modulator Design

After considering several alternate designs, the basic circuit of Fig. 3 has been chosen. In this circuit the pulse is generated in two segments - the leading edge is established by C_H and L_m, while the falling edge is determined by C_L and R_d. The value of the "low" voltage capacitor C_L is rather large but its operating voltage is on the order of 1 kV. In fact, the magnitude of V_L depends on the critical anode voltage of switch S_2, stray inductance L_s and peak current I_m.



I_m = 2252 A
t_r = 2.0 μs
τ_{ch} = 70 ms
τ_d = 3.5 ms

V_L = 1.0 kV $\quad C_H = \frac{1}{L_m}\left(\frac{2t_r}{\pi}\right)^2 = 0.27\ \mu F \quad i_{chH} = 0.04$ A

R_d = 0.444 Ohm

C_L = 7882 μF $\quad V_H = I_m\sqrt{L_m/C_H} = 10.6$ kV $\quad t_1 = 2.0\ \mu s$

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,..., is shown in Fig. 4. The augmented circuit employs a single bipolar high voltage section and n unipolar "low" voltage circuits (P1, N1, P2,...). Capacitor C_H is charged either positively or negatively with a bipolar high voltage power supply V_H and discharged into the load with one of the two 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 supplies. It also permits parallel charging of low voltage circuits in all modulators with a resulting simplification of the system pulse amplitude control.

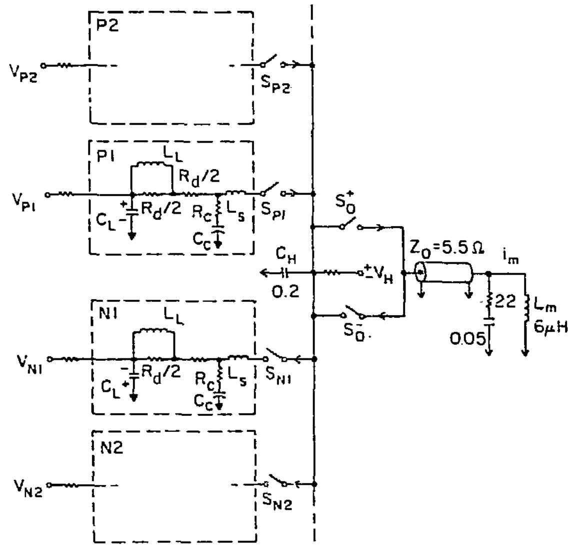


Fig. 4 The bipolar n-pulse modulator circuit

In each of the low voltage circuits of Fig. 4 there are three elements, R_c, C_c, L_L, which were omitted earlier for the sake of simplicity. The effect of L_L is to linearize the slope of the trailing edge of the pulse. The R_c-C_c circuit is used to improve pulse commutation between the high and the low voltage sections. The advantage of using L_L is in that it reduces the size of C_L for a given initial slope as well as the amount of charge transferred per pulse.

Simulation

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

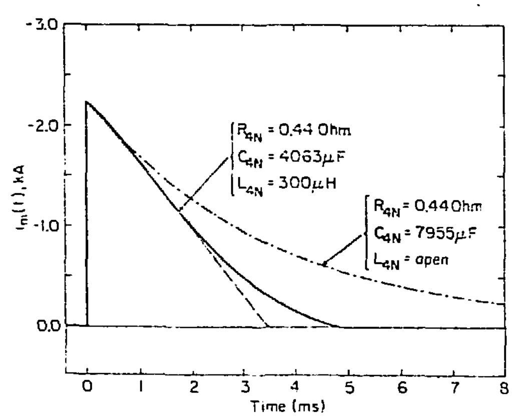


Fig. 5 Computed 4N pulse

The effect of stray inductance in the low voltage circuit on the shape of the front end of the same pulse is shown in Fig. 6. From the above results it is clear that in order to minimize the perturbation in the 4N pulse, the value of L_s must be less than 0.5 μH. In other circuits, where resistances R_d are larger, higher values of L_s may be tolerated.

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

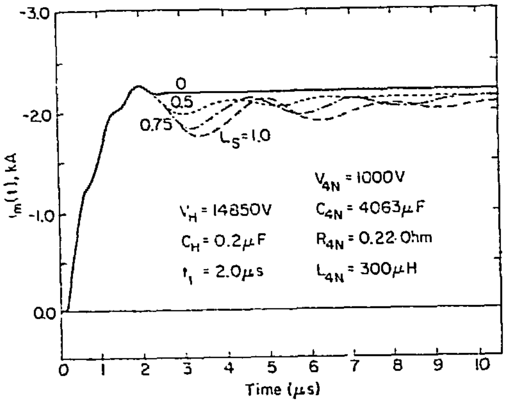


Fig. 6 The effect of stray inductance L_s on the front end of the pulse

Realization

The design of the system is based on twelve modulators, one bipolar 20 kV and eight monopolar 1.5 kV programmable charging supplies. Modulators are housed in separate buildings outside the machine tunnel and are connected to the magnets in the ring via coaxial pulse cables up to 200 ft long. All of the charging supplies are located in one of the buildings and are connected to the modulators with long charging cables placed around the ring as shown in Fig. 7.

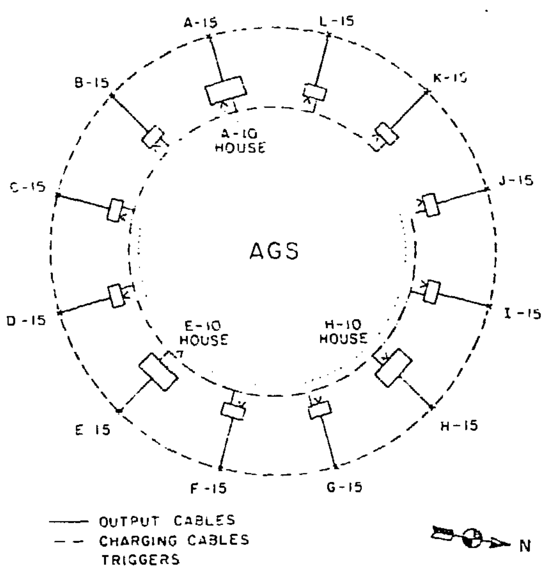


Fig. 7 Ps system layout

Each modulator is connected to the charging cables with a set of high voltage contactors. Hard wired interlocks and control circuits automatically disconnect the equipment from the charging cables in the case of a fault. The entire system is controlled with a network of microcomputers. System triggers are derived from a common source controlled by one of the micros.

In the modulators the high power switches are composed of EEV-1591 glass thyratrons and GE GL-37238 ignitrons. These thyratrons are an improved version of the EEV-1538 which has been successfully used in a pulsed application at Livermore. Ignitrons are used only in the output circuit and in five of the high current low voltage circuits. Thus there are ten thyratrons and seven ignitrons per modulator.

Triggers for each pair of tubes are obtained from a pulse transformer with two output windings. The output pulse cable consists of two 11-ohm low inductance double coax cables in parallel. Most of the high current interconnections in the modulators have been made with 5 in x 1/8 in busbars. Power resistors have been made up by paralleling a number of ceramic tubular resistors. A layout of components inside a modulator is shown in Fig. 8. A dummy load has been incorporated into each modulator to facilitate testing.

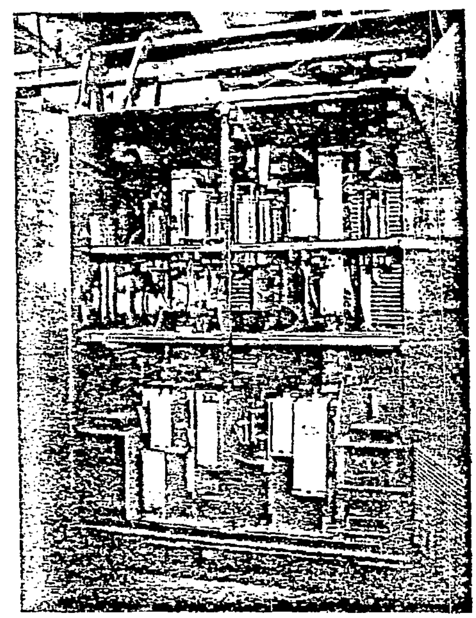


Fig. 8 Component layout inside the modulator

A prototype of the modulator has been built and tested in the fall of 1982/spring 1983. The first eight units were installed and successfully tested as a system during the first part of this year. All of the modulators have been built at BNL; the high voltage charging supplies were purchased outside.

Test Results and Operational Experience

The waveform of a magnet current pulse is shown in Fig. 9 and a three pulse test burst is shown in Fig.10. Commutation of current from the thyratron to the ignitron in one of the output tube pairs during a number of shots is shown in Fig. 11. The broad leading edge of the ignitron pulse is due to ignitron turn-on jitter. As can be seen, this effect is automatically compensated for by the thyratron so that the output pulse is stable.

The system of the first eight modulators has been used in the commissioning of the polarized proton project since the early part of this year. Since acceleration until now has been up to 10.3 Gev/c, only the first three pulses per burst have been used during operation. The remaining pulses will be required in the near future for acceleration to higher energies. So-far, each of the modulator output switches has accumulated several hundred thousand pulses with no recorded failures.

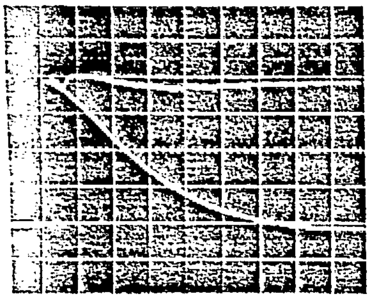


Fig. 9 A magnet current pulse

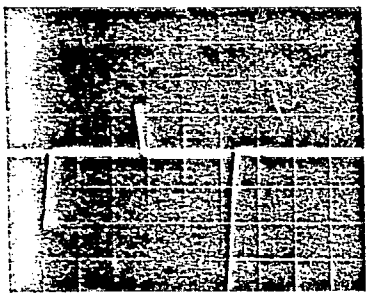


Fig. 10 A three pulse test burst

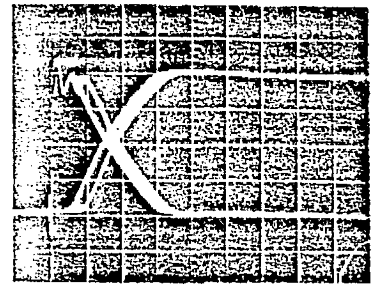


Fig. 11 Commutation of current from the thyratron to the ignitron in one of the output tube pairs

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References

1. R.J. Nawrocky and R.F. Lambiase, IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983, pp. 2772-74.