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SHAPED EXCITATION CURRENT FOR SYNCHROTRON MAGNETS*

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Summary

A 500 MeV synchrotron at Argonne National Laboratory (ANL) operates at 30 Hz with its beam spill locked to neutron choppers with a precision of ± 0.5 μs. The average beam will be increased by running the magnets at 45 Hz. Three 45 Hz circuits are discussed which differ greatly in overall cost and complexity.

The first is a conventional 45 Hz sine wave circuit. The reduction in time for beam acceleration results in a costly increase in peak RF power. This problem is avoided in the other two circuits by making the field rise slowly and fall rapidly.

The second circuit discussed is resonant at 45 Hz and 90 Hz. Exciting this circuit with a mixture of dc, 45 Hz, and 90 Hz can produce a magnetic field with the same maximum dB/dt as the present 30 Hz field.

A third, and possibly least expensive, solution is a novel circuit which produces 30 Hz during acceleration and 90Hz when the magnets are reset. The RF requirements are, of course, identical to present requirements during acceleration. Circuit details are given.

Introduction

The ring magnets of the 500 MeV Rapid Cycling Synchrotron (RCS) at ANL are excited with a dc bias of 2300 A modulated by a 30 Hz sine wave of 1300 A peak. An economical way to generate this current is with a 24-phase programmed power supply energizing a 30 Hz resonant circuit as shown in Fig. 1. The ring magnet is L_M = 28.8 mH, the choke L_{CH} = 16 mH and the condenser C = 3000 μF. The circuit losses are 475 kW and the power supply voltage is e = 137 V - 238 V sin 188.5t.

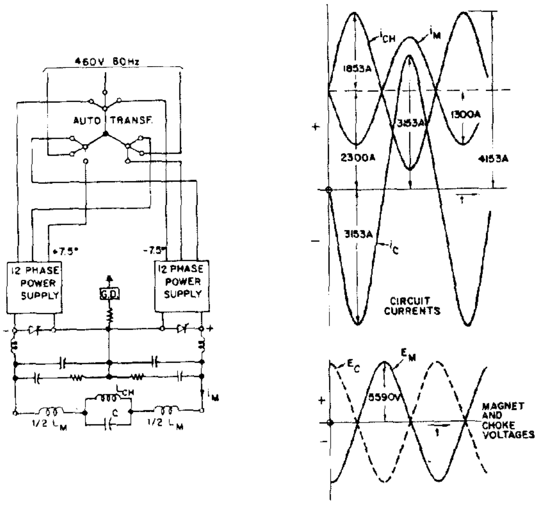

Fig. 1. Ring magnet power supply and waveforms of resonant circuit.

To increase the average beam, we will run the RCS at 45 Hz. Three magnet circuits employing three different magnet current wave shapes are presented.

45 Hz Sine Wave Magnet Excitation With New RF

The simple change to make in the magnet circuit is to tune the circuit for 45 Hz and drive it with a 45 Hz sine wave. The resonant circuit components are:

L_M = 22.8 mH R_M (DC) = 44 mΩ
L_{CH} = 80 mH R_{CH} (DC) = 36 mΩ
C = 705 μF R_C (45 Hz) = 23 mΩ
Power = 550 kW Peak Volts = 385 V

This circuit could be driven with our present power supply. The capacity required is much smaller, but the operating voltage is 50% larger. If the same condensers are used, we will require two in series by two in parallel or a total condenser requirement of 2820 μF. This plan calls for a new choke.

Unfortunately, the more rapid rise of the magnetic field is associated with much larger peak RF power requirements to accelerate the proton beam. The cost of the RF makes this magnet circuit unattractive. The circuits presented below avoid this problem.

45 Hz Plus 90 Hz Magnet Excitation

The RCS can operate without increasing the RF peak power if the maximum dB/dt is not increased. This is accomplished with a wave form using two harmonics:

$$B = \frac{B_{max} + B_{min}}{2} + \frac{B_{max} - B_{min}}{2} \times \left[\frac{8\sqrt{10}}{27}\sin(2\pi\ 45t) + \frac{5}{27}\sin(2\pi\ 90t)\right]$$

The shape of B versus t is the same as the shape of I_M versus time in Fig. 2a. The field is maximum or minimum when $\cos(2\pi\ 45t) = 1/\sqrt{10}$ and the slope has two maxima where $\cos(2\pi 45t) = -2/\sqrt{10}$. The proposed two-harmonic circuit and the current waveforms are also shown in Fig. 2a. The voltage waveforms are shown in Fig. 2b and the impedance versus frequency in Fig. 2c. The values for the circuit elements are:

L M. = 22.8 mH R, M. (DC) = 44 mΩ
L1 = 80 mH R, L1 (DC) = 20 mΩ
L3 = 35 mH R, L3 (45 Hz) = 50 mΩ
C2 = 357 μF R, C2 (45 Hz) = 45 mΩ
C3 = 176 μF R, C3 (45 Hz) = 90 mΩ
Power = 500 kW Peak Volts = 514 V

As with the single harmonic circuit above, the voltage on C2 makes it necessary to use two condensers in series and two in parallel if the available condensers are used. The voltage on C3 is even larger so that four in series and four in parallel are required. The total, using existing condensers, is 4250 μF. The major problem with this circuit is that the control problem becomes twice as complicated. This is shown schematically in Fig. 2d. Direct current must be regulated, as well as current and phase of each harmonic. The magnet circuit must be kept tuned to both 45 Hz and 90 Hz or the kVA will become excessive. Not only are there more factors to control, but also a precise control of the relative phase of the 45 Hz and 90 Hz is necessary to maintain the injection field and phase lock with the neutron chopper. The additional circuit losses make it necessary to add a third power supply. This allows one to more accurately produce the voltage wave shown in Fig. 2b with rectifier phase control. A 36-phase rectifier

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system is obtained by shifting, with an auto transformer, the 3-phase, 460 V input of two of the three identical 12-phase power supplies by ± 10°.

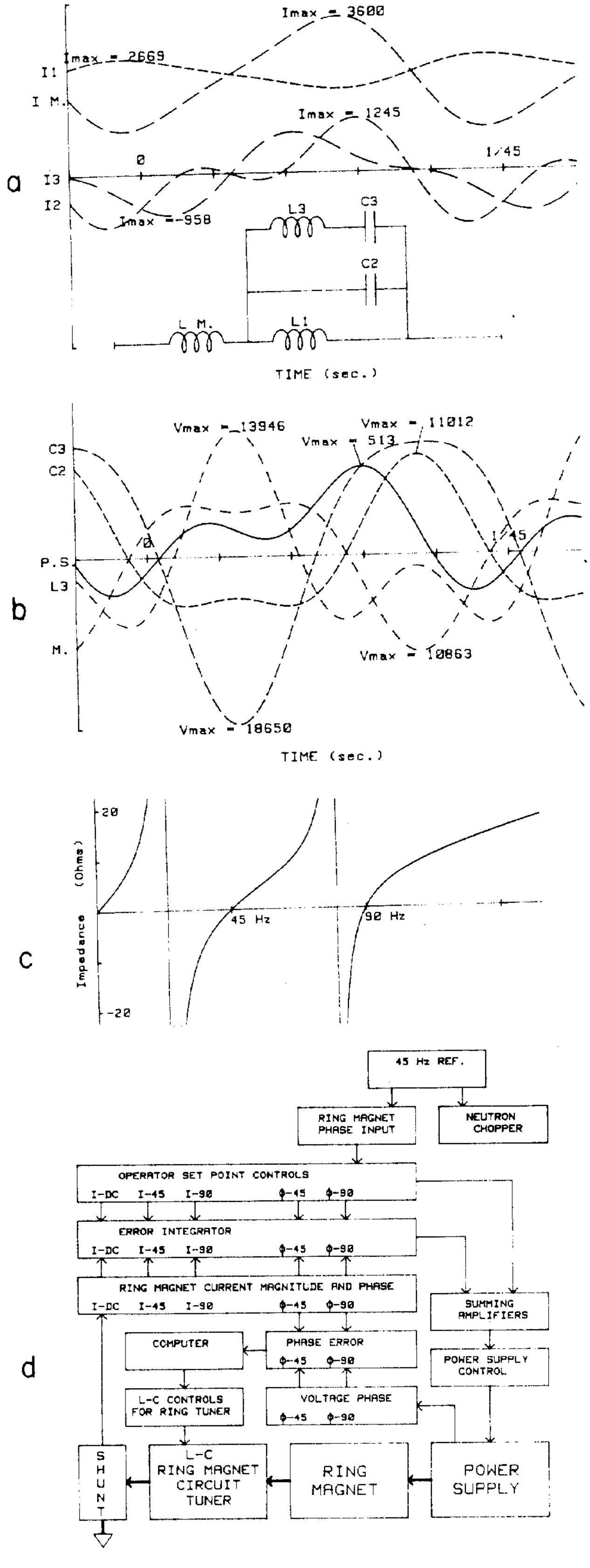

Fig. 2. 45 Hz plus 90 Hz excitation.

Accelerate With 30 Hz and Reset Magnet With 90 Hz

We nearly can have our cake and eat it with a third solution. During proton acceleration the synchrotron operates at 30 Hz utilizing the existing RF equipment. A repetition rate of 45 pps is achieved by resetting the magnet with a 90 Hz half sine wave. During this time, the RF is shut off. The magnet and capacitor voltage will increase during reset by a factor three. This is within the rating of the magnet and choke.

Figure 3 illustrates the circuit. At injection, switch S_1 is closed and the currents and voltages oscillate at 30 Hz. At the end of acceleration, the current in the capacitors is at its peak value. However, the energy in the capacitors is zero. If we now disconnect capacitor C_2, the circuit will reset with a 90 Hz half sine wave. During the reset, the peak voltage on capacitors C_1 exceeds the peak voltage during acceleration by a factor three. A new relatively small capacitor bank C_1, rated 12 kV rms, must be purchased. The solid state switch S_1 operates when:

- the current is at its peak,
- the voltage across it is practically zero,
- the forward voltage builds up at a rate of $dV/dt \leq \omega E \leq 565 s^{-1} \times 16.8$ kV ≤ 9.4 V/µs which is negligible.

The capacitor current in C_2 is zero when the switch closes at the end of the 90 Hz half cycle, and not at its peak value as required by the 30 Hz resonant circuit. This will cause a small transient because switching is done with very little transfer of energy; it requires not many ampere seconds to get a few kA into capacitors which are near zero voltage. Operation of the switch (repeatability, time jitter, etc.) is most critical before injection. Therefore, the switch should be closed shortly before the 90 Hz operation ends. It should be relatively easy to protect against circuit malfunctioning:

- If the switch fails to open, the circuit will complete its 30 Hz "low voltage" cycle.
- After a few 30 Hz cycles the RCS is again in phase with the 45 Hz chopper and the 30 Hz and 90 Hz operation can be resumed.

Switch S_1 is a bidirectional solid-state switch made from back-to-back SCR assemblies, SCR_1 and SCR_2, shown in Fig. 4. As seen in Fig. 3, a negative step change of capacitor current is initiated at time t_0 when SCR_1 is turned on. A quarter of a 30 Hz cosine wave later, this current is zero and SCR_1 turns off. At time t_1 a 0.5 ms long gate signal turns on SCR_2 and a positive sinusoidal current charges capacitor C_2. At time t_2, after a quarter of a 30 Hz sine wave, the capacitor voltage is zero and the capacitor current is at its maximum. At this time a turn-off circuit brings the current through SCR_2 to zero taking capacitor C_2 out of the circuit.

Circuit Description

For $t_o < t < t_1$ and $t = t_4^+$ -- As shown in Fig. 4a, SCR_1 is turned on and the choke current discharges at 30 Hz through the magnets and the parallel connection of C_1, C_2, and C_x. (Drawing the capacitor symbol in heavy lines indicates charge on the capacitor.)

At $t = t_1$ (Fig. 4b) -- The capacitor current goes through to zero ($i_M = i_{CH}$) and SCR_1 turns off. The capacitors are at 5.6 kV.

At $t_1 < t < t_2$ (Fig. 4c) -- With SCR_2 turned on, the capacitor current reverses.

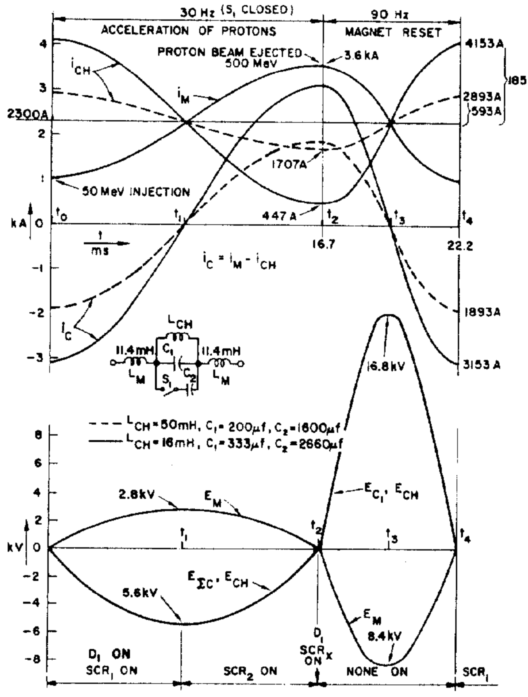

Fig. 3. Waveshapes for acceleration at 30 Hz and reset at 90 Hz.

At t = t_2 (Fig. 4d) -- The capacitor current is at its peak; the capacitors are discharged. At this time, SCR_X is turned on. This provides discharge paths for turn off capacitor C_X via SCR_X, SCR_2, and C_2 (current i_X') and via SCR_X, L_X, and C_1 (current i_X'').

At t = t_2 + 25 μs (Fig. 4e) -- The reverse current i_X' has turned off SCR_2. A resonant discharge of C_X via SCR_X, L_X, and C_1 continues for 80 μs (6.25 kHz).

At t = t_2 + 80 μs (Fig. 4f) -- The charge on C_X has reversed, i_X'' is zero and SCR_X turns off. In the next 80 μs capacitor C_X will reverse its polarity via C_1, L_X, and D_X. This charge, shown in Fig. 4g, remains on C_X because SCR_X is turned off and D_X blocks discharge. Thereafter, the solid state components will carry no current until t > t_4.

At (t_2 + 160 μs) < t < t_4 (Figs. 4g, 4h, 4i) -- The circuit resonates at 90 Hz. At t = t_3 the voltage on capacitor C_1 is at 16.8 kV and its current is zero. At t = t_4 the voltage on C_1 is zero and its current is at its peak. To assure a smooth transition from 90 Hz to 30 Hz operation at time t_4, a 0.5 ms gate signal is applied to SCR_1 0.1 ms before t_4.

In the circuit of Fig. 4 only ac currents are shown. For sake of clarity we have not shown a saturable time delay reactor to limit di/dt during turn-on of SCR_X; such a reactor may also be required to protect SCR_2 in case it turns on accidentally when C_1 is at a high voltage ($t \approx t_3$). Of course, other turn off circuits may be used. For example, capacitor C_X could be connected between the anodes of SCR_2 and SCR_X and charged from an independent low voltage dc supply; in this case, diode D_X is not required.

Reference

1. W. Praeg, D. McGhee, G. Volk, "Phase Lock of Rapid Cycling Synchrotron and Neutron Choppers," (Proceedings of this conference).

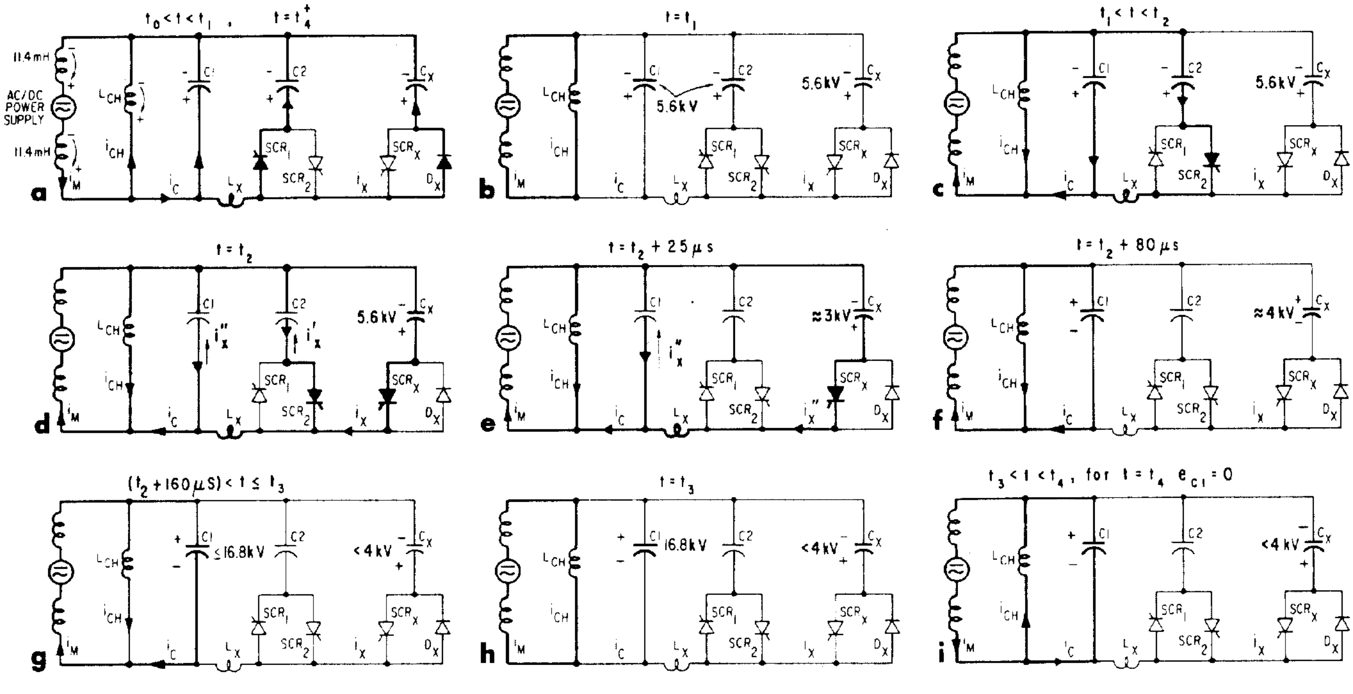

Fig. 4. Block diagram of resonant circuit for 30 Hz acceleration and 90 Hz reset.