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The 10 Hz Resonant Magnet Power Supply for the SSRL 3 GeV Injector*

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Abstract

The booster synchrotron for the recently commissioned SSRL Injector facility employs a 10 Hz resonant magnet power supply system to accelerate an electron beam from 120 MeV to 3 GeV. The booster dipole and quadrupole magnets are connected in series within a system of 17 distributed resonant cells driven by a pulsing network. Tracking power supplies driving the trim coils of the two quadrupole families are used to stabilize betatron tunes during energy ramping.

I. INTRODUCTION

A 10 Hz resonant magnet power supply system, or White Circuit [1], was chosen over a directly driven 2 Hz system for powering the SSRL Injector booster synchrotron in order to isolate the reactive power load of the cycling magnets from the AC mains distribution system at SLAC and SSRL. We viewed the White Circuit as being more simple, reliable, and better suited to our engineering expertise than other possible isolating systems such as mechanical flywheels, motor generators, and superconducting energy storage devices.

II. SYSTEM DESIGN CONSIDERATIONS

Four major design specifications were required to establish the basic White Circuit network: 1) the operating frequency; 2) the method of powering the quadrupoles; 3) the number of resonant cells and their configuration; and 4) the DC and AC power supply configuration.

A. Operating Frequency

The 10 Hz operating frequency was selected because 1) it would allow the use of 0.06" steel laminations for the booster magnet cores, costing significantly less than the more commonly used 0.025" laminations [2]; 2) it would permit the use of a thin (0.3 mm) stainless steel vacuum chamber; and 3) 10 Hz could be readily phase-locked to the line frequency, thus facilitating the stabilization of power supply noises at harmonics of 60 Hz. Also less beam intensity per/cycle would be needed to achieve a given SPEAR fill rate than for the 2 Hz system. Operating frequencies of 12 Hz and 15 Hz were considered, but they would cause more losses in the magnet cores.

B. Quadrupole Power

By connecting the quadrupole magnets in series with the dipoles in the White Circuit, we eliminated the need for a separate and carefully matched resonant power system for each of the two quadrupole families. On the other hand, this solution compelled us to implement quadrupole trim circuits so that betatron tunes could be stabilized during acceleration. Each trim circuit required a voltage-bucking transformer (or choke) of size and cost comparable to that for the inductor that would have been needed for an independent resonant circuit. The main advantage of this system was one of control and ease of matching the current waveforms in all magnets.

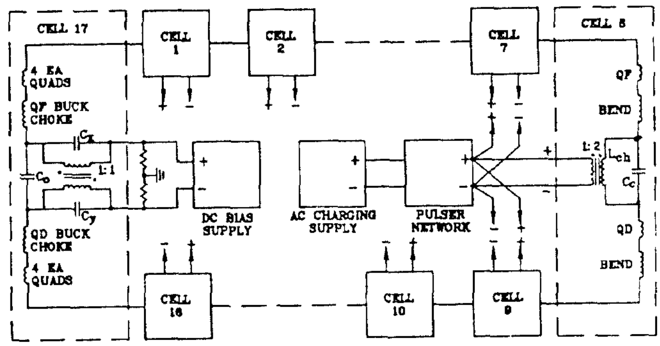

Figure 1. 17 cell White Circuit for the SSRL Booster

C. Resonant Cell Configuration

A distributed multiple cell White Circuit design was chosen 1) to solve an equipment space problem by distributing the energy-storing chokes and capacitor banks under the booster magnet girders; 2) to avoid the difficulty of engineering and fabricating a single massive choke that would weigh close to 50 tons; and 3) to limit the induced AC voltage level in the system.

To simplify coil insulation design and to enable us to use readily available semiconductor components, we decided to limit the peak AC + DC voltage difference between any system component and ground to 2 kV or less. This implied that no more than two dipoles and some number of less inductive quadrupoles should be included in a cell. Since the lattice had 32 dipoles, 16 cells were needed for them. A 17th cell was required for the two quadrupole bucking chokes and 8 of the 40 quadrupoles that were not in the dipole cells.

D. Power Supply Configuration

A final major design decision was to separate the sources of DC and AC power for the White Circuit and to drive the 10 Hz current oscillation through transformer windings on the cell chokes. We were wary of using a combined AC and DC supply system connected in series with the magnets because 1) we anticipated difficulties in injection at low energy due to magnet current disturbances, possibly including the transmission line or standing wave modes [3], driven by high frequency noise and ripple in

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the voltage sourced by the series-connected rectifier supplies; and 2) it would not be possible to operate the circuit in an underbiased mode unless the supply were capable of inversion, a capability that would be accompanied by higher voltage ripple.

We further reduced the level of current disturbances at injection by implementing a pulsed AC power system as opposed to one that would continuously drive the 10 Hz oscillation. A pulsing network [4] was designed to generate a 17 msec current pulse to the cell chokes while the magnet current was decreasing and no beam was in the machine. Transient current disturbances caused by the pulse would damp out before new beam was injected and the accelerating current waveform would be noise-free.

III. WHITE CIRCUIT IMPLEMENTATION

A. Network Configuration

Figure 1 depicts the 17 cell White Circuit design for the SSRL separated function booster lattice. The 17th cell is configured to permit insertion of the DC bias current from a voltage-regulated DC power supply; a split coil configuration of the cell choke enables it to be used as part of the balanced 10 Hz blocking filter for the supply. The 10 Hz circuit resonance is driven by coupling the output power from the 10 Hz pulser through transformer windings on the 16 standard cell chokes. Component and system specifications for 3 GeV operation are summarized in Table I.

The 16 cell chokes are connected to the pulser with equal length cables in a star configuration; this configuration ensures the equalization of impedances between pulser and cells and between any two cells. Equalization of pulser-cell impedances is necessary for the uniform and nonreactive distribution of power to the circuit. Cell-cell equalization maximizes the even distribution of circulating currents between cells when one becomes mistuned and thus helps equalize the otherwise imbalanced cell voltages. The 17th cell is not pulsed in order to avoid driving the pulse current through the DC bias supply.

The values for cell capacitance and choke inductance were determined by minimizing the estimated total cost for capacitors and chokes assuming a that the cost per joule for capacitors would be a little more than twice that for chokes. The actual cost ratio turned out to be ~2.2.

Table I. 10 Hz White Circuit Parameters at 3 GeV

COMPONENT	QTY	VALUE		RATING	DC/AC PS kW
Dipole	32	21.1	mH	630 Apk/380 ARMS	2.4/2.9
QF	20	1.0	mH	" / "	.46/.43
QD	20	0.8	mH	" / "	.40/.36
Buck Choke	2	20.0	mH	" / "	3.9/5.0
Cell Choke	17	80.0	mH	500 Apk/345 ARMS	7.8/4.1
Cell Cap	16	8.9	mF	640 VRMS	0/0.5
Cell 17 C_o	1	5.8	mF	2 kV pk	0/1.0
Cell 17 $C_{x,y}$	1 ea	6.3	mF	320 VRMS	0/0.2
Charge Choke	1	250	mH	273 Apk/210 ARMS	0/5.0
Pulse Choke	1	2.0	mH	4 kApk/1.2 kARMS	0/10
Pulse Cap	1	14.2	mF	2 kV pk	0/2

DC Bias PS:	735	VDC @ 320 ADC	DC Pwr: 235 kW
AC Charging PS:	1020	VDC @ 273 Apk/210 ARMS	AC Pwr: 215 kW
Circuit Q:	28		

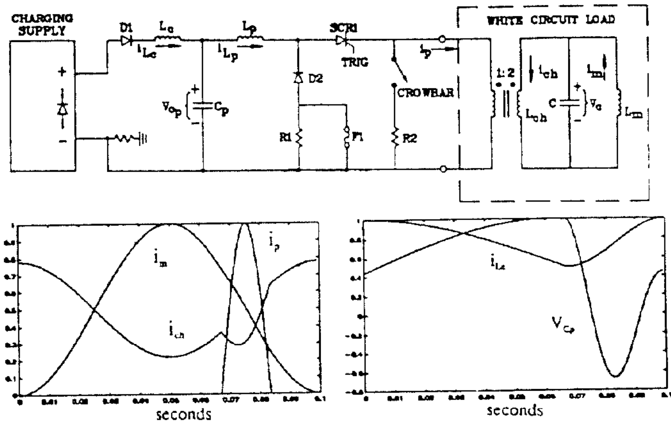

Figure 2. Pulser network and circuit waveforms

A bucking choke is needed for each quadrupole family in order to cancel the voltage induced on the trim coil circuit by the main coil circuit and vice versa. The primary windings of this choke are connected in series with the quadrupole trim windings, while the secondary windings are connected antiphase in series with the main coils. The mutual inductance of the bucking choke must match the sum of mutual inductances of the quadrupole main/trim coil transformers for proper operation.

B. Pulser Network

The 10 Hz pulsed power system is shown in figure 2. It consists of a capacitor bank C_p that is resonantly charged from a DC voltage regulated power supply through a charging choke L_c and discharged through a pulse choke L_p when SCR1 is triggered. The resonant discharge frequency is 30 Hz; current conducts through SCR1 during the first half cycle of this oscillation, providing ~17 msec wide current pulse to the parallel-connected choke primary windings. When the current pulse falls to 0 A, SCR1 stops conducting and the voltage across C_p is negative. This voltage drives a 30 Hz negative current half cycle through L_p via F1 and D2 that partially recharges C_p to a positive voltage. Full recharging of C_p is completed by current from the charging supply through L_c. In the event of a circuit fault where SCR1 latches on or otherwise conducts during the wrong phase of the 10 Hz cycle, F1 will blow and R1 will serve to limit the current in diode D2 and SCR1 to a nondestructive level for those semiconductor devices.

The resonant frequency of the recharging circuit is ~2.5 Hz so that the capacitor voltage has not quite reached an oscillation maximum when the 10 Hz trigger is applied. This ensures a continuous non-zero charging current and reduces the transient current loading on the power supply.

C. Chokes

The dimensional envelope of the cell choke was determined by the available space under the magnet girders in the booster tunnel. The core and air gap configuration was designed using the POISSON magnet modeling program to maintain a constant inductance to within $\pm 0.5\%$ over its full range of current energization for up to 3.5 GeV operation. The core design, shown in figure 3, has the advantage that it was relatively easy to fabricate and was readily tunable so that the same core design could be

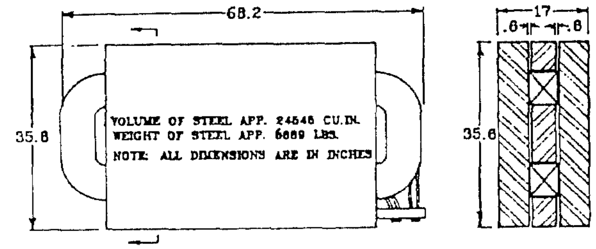

Figure 3. White Circuit cell choke

used for both the charging and bucking chokes by adjusting the gap height. It has the disadvantage that stray fields leak from the air gaps in the side legs and disturb CRT displays and some other types of sensitive instrumentation.

As was done for the 10 Hz magnets, the cell, charging, and bucking choke cores were fabricated using 0.06" 1005 steel laminations [2]. The resulting AC power dissipation in the circuit was approximately twice what it would have been if 0.025" electrical steel laminations had been used.

The 30 Hz pulse choke has 0.025" core laminations stamped from the same die used for the booster dipole laminations. It too has air gaps in the side legs, but only at the center parting plane of the upper and lower core halves. The middle and side end poles are tapered in an approximate Rogowski contour to reduce heating and magnetic forces that tend splay the end laminations.

D. *Capacitors*

Each cell capacitor bank is configured from a set of six 5700 μF capacitor groups together with one trimmer group. Three parallel-connected groups are connected in series with the other three parallel-connected groups; the trimmer group is connected in parallel with this total assembly and adjusted to form the 8900 μF nominal capacitance needed for 10 Hz operation. The groups can be rearranged in a 2-parallel, 3-series pattern for 15 Hz operation.

Each 5700 μF group is comprised of 60 each 95 μF capacitor units connected in parallel and mounted on a tray that, together with the five other similar trays and one trimmer tray, slides into a cabinet that fits under a booster magnet girder.

The trimmer tray consists of binary-weighted groups of capacitor units that can be switched in and out to tune the resonant cell. The trimming resolution is 0.6% of the total cell capacitance, permitting a frequency tuning resolution of 0.3%.

The cell 17 capacitor banks C_x, C_y and C_o, and the pulser capacitor bank C_p are also configured using capacitor trays, but in these cases they are all connected in parallel. The cell 17 capacitor banks each have trimmer trays with trimming resolutions similar to that for the cell banks. The individual capacitor units for C_o and C_p are rated for peak voltages of 2.2 kV and 2.7 kV respectively, adequate for both 10 Hz and 15 Hz operation.

All capacitor units are fabricated using metallized polypropylene and consequently have a low temperature coefficient that limits the thermal drift in resonant frequency to less than 0.4% over a 25°C range.

E. *Power Supplies*

Two 480 kW voltage regulated power supplies are used to power the White Circuit. Both are 12-pulse SCR controlled supplies rated for 1200 VDC, 400 A service with 480 VAC mains input. The DC Bias supply has a 7 Hz L-C low pass output filter to reduce the output ripple voltage Hz to less than 1 V pk-pk. This ripple specification ensures that magnet bias current ripple will be 0.1% or less of the 25 A injection current. The Charging supply does not require the output filter since L_c and C_p in the pulser network perfrom this function. The effects of harmonic voltage ripple are further reduced by phase-locking the 10 Hz circuit trigger, and thus the magnet current oscillation, to 60 Hz [5].

The injection current is stabilized to the 0.1% level, well within the 0.5% energy acceptance of the booster, by deriving the linac trigger timing from a biasable peaking strip installed in a booster dipole [5]. The peaking strip generates a timing pulse when the injection magnetic field threshold is reached, relieving the regulation requirement for the power supplies that would otherwise be on the order of 0.01% of their output currents. Instead the supplies are regulated to the order of 0.1% so that the extraction current and beam energy will be stable to that level.

The quadrupole tracking supplies are configured using pulse width modulated bipolar servo amplifiers powered from a common 300 V bulk supply. Each amplifier can be programmed to source up to 60 A peak current, 10% of the 3 GeV main coil energization, and has a bandwidth of ~300 Hz. The regulation requirement is again on the order of 0.1% to meet injection stability needs.

IV. OPERATIONAL EXPERIENCE

The White Circuit has been proven to be a reliable and relatively simple system to operate during its several months of 2.35 GeV operation. Most of the commissioning effort was devoted to repairing coil and core vibration problems in some of the magnets and chokes and to improving the high power operation of the power supplies. Since then, end laminations on some of the choke cores have come loose and occasionally a capacitor fuse must be replaced. 3 GeV operation is scheduled for 1992.

The magnet current waveform during the ramp is observed to be free of harmonic contamination. This coupled with the injection current stability obtained with the peaking strip and the tune stability achieved with the quadrupole tracking system contributed greatly to the success of the White Circuit in meeting the Injector facility goals.

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