DRAFT January 25, 1979

UPC 084

Notes for Energy Doubler Correction Element Power Supplies

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I. Dipole and Sextupole Correction

The proposed correction element system utilizes 180 dipole trim windings and 180 sextupole trim windings. Each of the 360 windings must be independently controlled, necessitating independent power supplies. The required current is ±50 A and accuracy is ±0.1% of full scale current (i.e. ±.05 A). The power supply would be designed with load compensation and have a conventional roll-off characteristic as shown below.

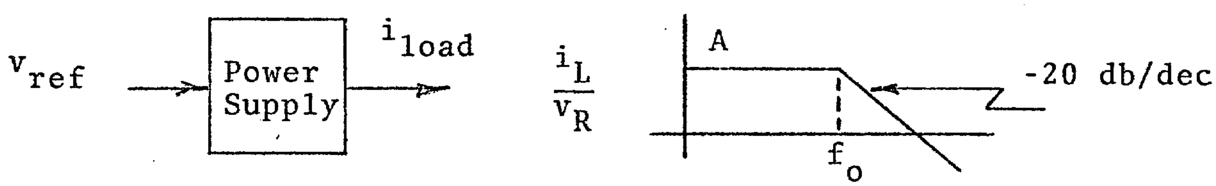

Figure 1. Power Supply Characteristics

Load inductance would be in the range of 20-100 mh.

To complete the power supply requirements the bandwidth (BW) and voltage must be determined. It is reasonable to have a BW which allows the power supply output to follow a constant ramp input within ±0.1%. For the power supply described thus far

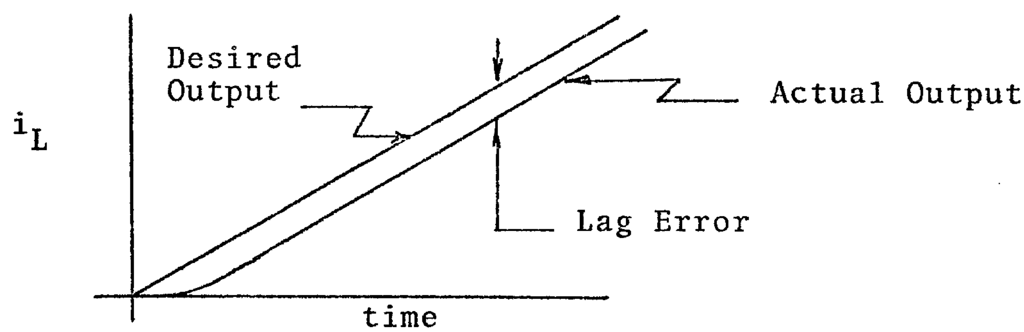

Figure 2. Power Supply Ramp Response

the error between programmed input and power supply output for a constant ramp is given by equation 1.

$$\varepsilon = \frac{AB}{2\pi f_o} \quad \text{(amps)} \tag{1}$$

where

ε = Lag error (amps)

A = Power Supply DC Gain (amps/volt)

B = Input voltage ramp rate (volts/sec)

f_o = Power Supply BW or corner frequency (Hz)

For a maximum error of .05 A and an Energy Doubler ramp rate of 10 seconds, a BW of 20 Hz is probably adequate. The maximum ramp rate allowable under these conditions with A = 10 amps/volt is

$$B(\max) = \frac{2\pi f_o \varepsilon}{A} = \frac{2\pi(20)(.05)}{10} = .628\text{V/sec.} \tag{2}$$

The maximum output ramp rate for 0.1% accuracy is:

$$(0.628 \frac{\text{volt}}{\text{sec}})(10 \frac{\text{amp}}{\text{volt}}) = 6.28\text{A/sec} \tag{3}$$

If the ramp rate and power supply gain were unchanged and .01% accuracy was necessary during the ramp, the power supply BW would have to be 200 Hz.

The dipole and sextupole power supplies would be installed in the existing main ring service buildings with 12 power supplies per building. It is expected that the power supplies would be put in standard 19" racks with 4 to 6 power supplies per rack. The longest lead from power supply to the correction winding and back would be 1000 feet. Using #2 or #4 wire, the voltage drop at 50 A and 50°C would be 8.8 or 14 V respectively. To meet 0.1% accuracy the magnet current rate-of-change should not exceed 6.28 A/sec. Therefore, a maximum slew rate of 10 A/sec is probably adequate. If L = 100 mh, the maximum voltage across

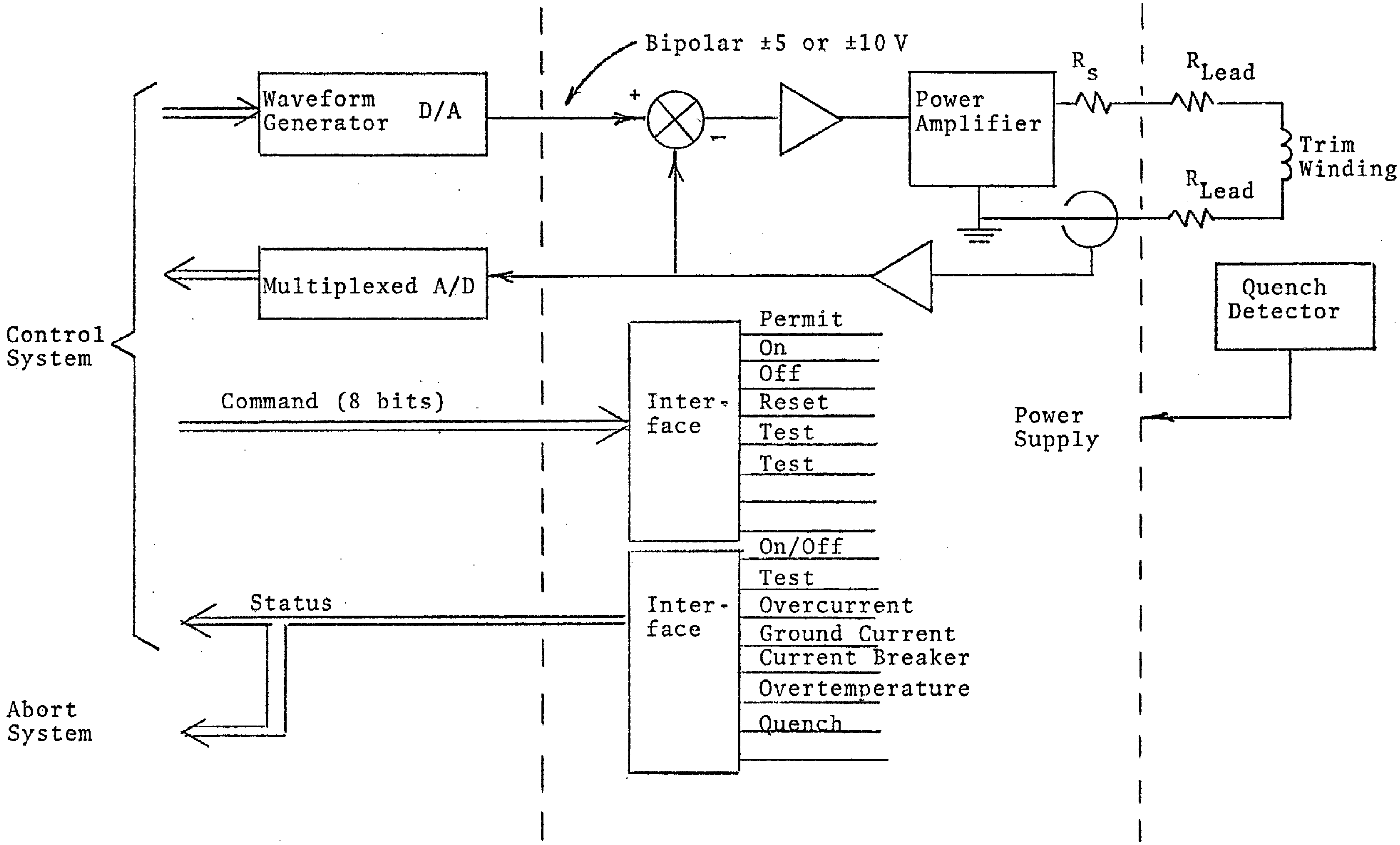

Figure 3. Energy Doubler Dipole and Sextupole Correction Power Supply System

the winding is

$$v = L\frac{di}{dt} = (.1h)(10\frac{A}{sec}) = 1 \text{ volt.} \qquad (4)$$

Adding the resistive and inductive load requirements shows that the maximum power supply output voltage falls in the range of 10 to 15 volts.

A typical dipole or sextupole correction supply is shown with connections to the control system and load in Figure 3. The control system provides a bipolar analog reference waveform from a generator with 12 bit resolution and 8 bits for commands to operate and check each power supply. The analog current signal is sent to the control system multiplexed A/D along with 8 status and fault bits. Isolation is provided between the control system and power supply for command, status and faults by means of optical couplers. Isolation of the analog signals between the power supply and control system is not felt necessary at this time.

A quench detection and protection system is provided for each winding to prevent unnecessary dumping of energy in the cryostat. Two approaches have been considered as shown in Figure 4. In Figure 4a, after a quench is detected, the output

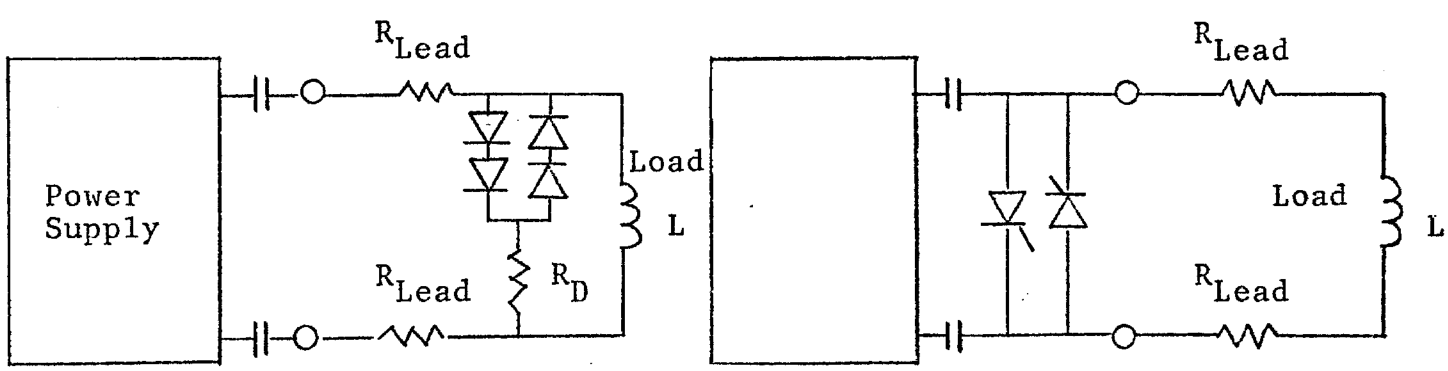

Figure 4. Possible Quench Protection Schemes

contactor is opened and the load current decays through a pair of diodes and R_D. Under normal operation the voltage component across the load is not large enough to forward bias the diodes sufficently to draw 50 mA (0.1% of full scale current). The diodes and resistors are located in the tunnel. In Figure 4b, after a quench is detected, the shunt SCR's are fired, the output contactor is then opened and the load discharges through one of the SCR's and the power supply leads with a time constant of $L/2R_{lead}$. The shunt SCR's are located in the power supplies.

The requirements of a bipolar power supply rated at ±10 or ±15 volts, ±50 A, ±0.1% accuracy and ripple, and BW = 20 Hz can be met with either an SCR controlled dual converter or a transistorized power amplifier. Either approach would use series output resistors or other techniques to compensate for lead resistance variations, to keep load L/R constant for maximum performance. The cost for either power supply with quench protection appears to be about the same at $2000 each. An exact cost advantage of one approach over another cannot be determined without a detailed cost analysis based on specific designs. Other factors such as noise, cooling, space, voltage isolation, weight, and efficiency will possibly affect the approach chosen. The installation costs for each power supply, considering cable, labor, rack space, and connection to building power is estimated to be $540 each. Notice that use of existing cable trays and existing building power service is assumed. Thus the estimated cost of construction and installation, neglecting engineering costs for the 360 power supplies is as follows:

Power Supply cost	\$2000 x 360 =	\$720,000
Installation cost	\$ 450 x 360 =	162,000
		\$882,000

If the power supplies had to be up-graded to a state-of-the art device with ±.01% or ±0.005% regulation, ripple and accuracy the cost of each power supply would increase substantially. The high precision power supply would look slightly different that that shown in Figure 3. The bipolar waveform generator should have 16 bit accuracy and be located within the power supply to limit noise. The current monitor would be a precision transductor with a ±10 volt output. Stability of the waveform generator and DCCT would each have to be on the order of 1 ppm/^{o}C of full scale. The required low temperature coefficient can be achieved with an Analogic MP8116 16 bit D/A and a Hazemeyer high precision ±50 A DCCT. For each precision power supply the cost would increase about \$2000. The tight regulation specification would require power supplies to have a BW of 200 to 400 Hz. SCR-type power supplies would be impractical. Only a transistorized power amplifier could meet the stringent requirements.

II. Octupole Correction

The octupole correction system is comprised of 180 octupole correction windings arranged in 8 series circuits. Each circuit is powered by a separate high precision, state-of-the-art power supply rated at ±50 A. The desired accuracy and stability during extraction is ±.005% to ±.01% of full scale current. Each octupole correction winding is assumed to have an inductance of about 23 mh. The power supply would have load compensation and have a conventional roll-off characteristic as shown in Figure 1.

Although final programmed waveshapes have not yet been established, reasonable estimates of the power supply voltage and BW requirements can still be made. Presently the octupole corrections are only required during extraction. However, from a control standpoint it would be desirable to ramp the octupoles to their extraction level current during the accelerator ramp time. The current tolerance during the ramp would be less stringent, say ±0.1%. During extraction, the octupole current would be held constant at ±.005 to ±.01%. The ramping and extraction accuracy requirements could probably be met by a power supply with a BW of 20 Hz. However to obtain the required low ripple current, a transistorized output regulator would be necessary. In which case, a BW of 100-200 Hz should be achieveable at no extra cost. With a higher BW, some programming with high accuracy during extraction is thus possible.

The maximum power supply voltage can be calculated knowing the maximum ramping rate and the load resistance in each series circuit.

If the octupoles were ramped to 50 A in 8 sec, the load current would change at 6.25 A/sec. Assuming that no more than 24 windings are in any series load connection, the maximum inductive load voltage is found to be 3.5 V.

$$v_L = L\frac{di}{dt} = (24x.023\ h)(6.25\ A/_{sec}) = 3.5\ V. \qquad (5)$$

The octupole power supplies would be installed in every third service building around the main ring (e.g. A1, A4, B3, C2, etc.). Assuming that the octupole correction leads are brought out of the cryostat at each correction package, approximately 5480 feet of cable is required to interconnect each string of windings. Using #2 cable, the resistance at 50°C is .964Ω and the voltage drop at 50 A is 48.2 volts. Thus the total required compliance voltage of the power supply would be 3.5 48.2 volts = 51.7 volts.

The octupole correction power supply would be configured much like the dipole supply shown in Figure 3 with a few exceptions. First the waveform generator would be a precision 16 bit D/A (Analogic 8116 or similar device) with ±10 volt output and located within the power supply to minimize noise pickup and provide the highest accuracy possible. Second the current sensor would be a precision DCCT with ±10 volt output (Hazemeyer ±50 A). And last, the trim winding shown would actually be many trim windings in series.

The quench protection schemes considered are shown in Figure 4. Each of the octupole windings would have a quench detection circuit whose outputs would be brought back independently to the power supply or placed in a series circuit with only 2 wires returning to the power supply. Once a quench was detected at the power supply, the entire string of windings would be dumped by opening the output contactor as in Figure 4a or by firing bypass SCR's and opening the output contactor as shown in 4b. In Figure 4A, R_D would be limited so that excessive voltage to ground does not develop across the winding string and to protect the output conductor. Without any resistance, $R_D = 0$, the load current in each winding would decay to OA in one second or less. In Figure 4a, the diode leakage current during the ramp with $v_L = .144$ V would be less than 2.5 ma for ±.005% accruacy.

The octupole power supply requirements are summarized as follows: ±50 A, ±52 V, ±.01 to ±.005% accuracy, and BW = 100 to 200 Hz. To meet these requirements, the output supplies would use 2 commercially available, fixed-voltage power supplies to provide low ripple, regulated power to a bipolar-output, transistorized regulator. The output transistor requirements are not excessive and cooling could be accomplished with either water or forced air. Each octupole supply would occupy approximately 1/2 to 3/4 of a 19" rack. The octupole supply cost including commercially available power supplies, precision D/A and DCCT, quench protection, and other miscellaneous items is estimated to be $6850 each. Installation including cable, labor, rack space and connection of the supply to building power is estimated to be $3500 each. Thus the estimated cost of construction and installation of the 8 octupole correction supplies neglecting engineering cost, is as follows:

Power Supply Cost	$6850x8 =	$54800
Installation Cost	$3500x8 =	$28000
	TOTAL	$82800

III. Quadrupole Correction

The quadrupole correction system is comprised of 180 independent quadrupole windings arranged in 8 series circuits similar to the octupole correction circuits. Each of the circuits is driven by a ±50 A, high precision (±.005% to ±.01%) power supply. The inductance of each quadrupole winding in the string is about 300 mh. The power supply would have load compensation and a conventional roll-off characteristic as shown in Figure 1.

The quadrupole correction elements must be ramped during acceleration similar to the dipoles, but the tight ±.01% regulation is not necessary. A maximum ramping rate of 6.25 A/sec (50 A in 8 sec) is probably adequate. During extraction the tightest regulation tolerances possible will apply while the load current is required to change by 2% in 10 sec (i.e. 0.1 A/sec). Again a 20 Hz bandwidth requirement is probably sufficient, but to achieve the necessary low ripple a transistorized output regulator is recommended. With the transistorized output regulator, a 100-200 Hz bandwidth can be expected and as a result, tolerances better than ±.1% can be achieved during acceleration.

The power supply voltage requirements can be estimated from the maximum ramping rate of 6.25 A/sec and the resistance of the series circuit. One of the quadrupole correction supplies would be located in every third main ring service building (e.g. A2, B1, B4, etc.). Approximately 5480 feet of cable is required to connect the windings in each string to the power supply. Using #2 cable, the load resistance at 50°C is .964Ω. At 50 A the resistive load voltage is 48.2 V. Assuming that there are no more than 24 quadrupole windings per series circuit, the maximum inductive voltage is 45 V. The total required compliance voltage at the power supply is 93.2 V.

The quadrupole correction supply would be the same as the octupole supply in most respects, including precision 16 bit D/A and DCCT. However, the output voltage is higher, approximately 100 V, and as a result, the output transistor regulator becomes large under some operating conditions. To reduce the transistor bank dissipation, the quadrupole correction supply would use programmable, commercial supplies to provide well filtered, regulated voltage to the output transistor regulator. The programmable supplies would be operated to keep a nearly constant voltage across the output transistor banks and thus reduce the transistor bank requirements. By careful design, the transistor bank regulator for both the octupole and quadrupole correction supplies could be the same. The main difference then would be in the choice of the commercial supplies for the octupole and trim correction systems.

Quench protection for the quadrupole correction windings would use the same scheme as for the octupole windings. The voltage across each winding during acceleration is

$$v_L = L\frac{di}{dt} = (.3)(6.25\ \text{A/gec}) = 1.875\ \text{V}$$

and thus in Figure 4a, 4 or 5 diodes must be used in series across each winding to keep diode leakage at an acceptable level. Thus if a quench occurs during extraction the voltage across the quadrupole correction winding will rise to a higher voltage than other correction windings before being clamped by the diodes. Winding discharge time would be about 2 seconds. Tests will be performed on quadrupole correction windings to determine if the higher voltage level is permissible. Alternately, the scheme shown in Figure 4b as described for the octupoles can be used.

The quadrupole correction supply cost including commercially-available, programmable power supplies, precision D/A and DCCT, quench protrection, and other miscellaneous items is estimated to be $10,450 each. The correction supplies can be expected to fill 50% to 100% of the space in a 19" rack. Installation cost including cable, labor, rack space, and connection to building power is estimated to be $3500 each. Thus the construction and installation costs, excluding engineering costs, can be summarized as follows:

Power Supply Cost	$10,450 x 8 =	83,600
Installation Cost	$ 3,500 x 8 =	28,000
TOTAL		$111,600

IV. Summary

The major correction element power supply costs have been itemized and the various correction element power supply systems described. Other trim-type power supply requirements, however, for special purposes can be expected to arise. These may be in the order of 30 of these special supplies distributed throughout the ring. Assuming they are ±50 A and power independent correction elements, a per unit cost of $2500 can be expected. Thus the total cost of the correction element power supplies including installation is summarized below.

180	Dipole Correction Supplies	$441,000
180	Sextupole Correction Supplies	$441,000
8	Octupole Correction Supplies	$ 82,800
8	Octupole Correction Supplies	$111,600
30	Miscellaneous Correction Supplies	$ 75,000
	TOTAL	$1,151,400

It should be pointed out that all power supply ripple requirements discussed in these notes are based on the assumption that the beam pipe and other structural members do not reduce ripple current effects.

This may not be valid. The current/field transfer characteristic should be measured to determine actual power supply requirements for such things as current ripple.