Chapter 7. Power Supplies

Cezary Jach and Dan Wolff

7.1. Introduction

The Proton Driver power supply system consists of a dipole/quadrupole power supply system, a quadrupole tracking and correction power supply system, a dipole horizontal and vertical correction power supply system and a sextupole power supply system. This Chapter also describes preliminary design of the power distribution system supplying 13.8 kV power to all Proton Driver electrical systems (in Section 7.7).

The power supply system is designed to provide current to the magnets in the form:

$$I(t) = I_{dc} - I_{ac} \cdot \cos(2\pi 15t) + 0.125 \cdot I_{ac} \cdot \sin(2\pi 30t)$$

where: I(t) is the magnet current, I_{dc} is the dc component of the magnet current and I_{ac} the a.c. component.

A second harmonic (30 Hz) is added to the fundamental to reduce dB/dt in the magnets during acceleration. A 12.5% second harmonic component results in a 25% reduction in dB/dt.

Since all Proton Driver magnets are designed to operate at 16 GeV, all magnet power supply system components have been designed to operate at this level. These include interconnecting bus, terminals, LCW water system, bucking chokes, power supplies, controls and regulation systems. Infrastructure (service buildings, equipment pads) and the 13.8 kV power distribution system are also designed to accommodate 16 GeV operation. Energy storage devices (resonant cell chokes and capacitors) for the dipole/quadrupole resonant network are designed to operate at 12 GeV and can be fully utilized in the 16 GeV configuration using the upgrade described in Section 7.2.4.

7.2. Dipole and Quadrupole Power Supply

7.2.1. System Requirements

The system requirements are listed in Table 7.1.

Table 7.1. System Requirements

	Stage 1 12 GeV Operation	Stage 2 16 GeV Operation
Repetition rate	15 Hz	15 Hz
Maximum magnet current, I_{max}	4,820 A	6,317 A
Minimum magnet current, I_{min}	356 A	356 A
I_{dc}	2,546 A	3,337 A
I_{ac} (15 Hz)	2,274 A	2,980 A
0.125 I_{ac} (30 Hz)	284 A	373 A
$\Delta I/ I_{max}$	0.01%	0.01%
Dipole number of electrical turns per pole	12	12
Dipole inductance	2.88 mH/m	2.88 mH/m
Length of long dipoles	5.25 m	5.25 m
Number of long dipoles	36	36
Length of short dipoles	3.94 m	3.94 m
Number of short dipoles	12	12
Total Length of Dipoles	236.3 m	236.3 m
Total Inductance of Dipoles	680.5 mH	680.5 mH
Quadrupole number of electrical turns per pole	4	4
Quadrupole inductance	1.48 mH/m	1.48 mH/m
Total length of quadrupoles	132.4 m	132.4 m
Total inductance of quadrupoles	196.0 mH	196.0 mH
Beam pipe losses	1.10 MW	1.97 MW

7.2.2. System Design

The choice of the magnet resonant network configuration is influenced by three factors: the need to avoid drawing a large reactive power from the a.c. line, reliability, and the importance of maintaining equal currents in the magnets.

The circuit in Figure 7.1 satisfies these basic requirements. The diagram shows three typical resonant cells adjacent to the power supply. Dipoles, F-quadrupoles and D-quadrupoles are connected in series. Power supplies are inserted in series with the magnets near the virtual ground of the distributed resonant circuit. Each power supply is a source of a.c. and d.c. power (similar to the Fermilab Booster). Dividing the resonant system into 30 resonant cells permits a significant decrease in the system voltage to ground. The magnet (L_m), capacitor banks (C and C_1), and chokes (L_{ch}, and L_1), form a resonant cell. Its frequency response is shown in Figure 7.2.

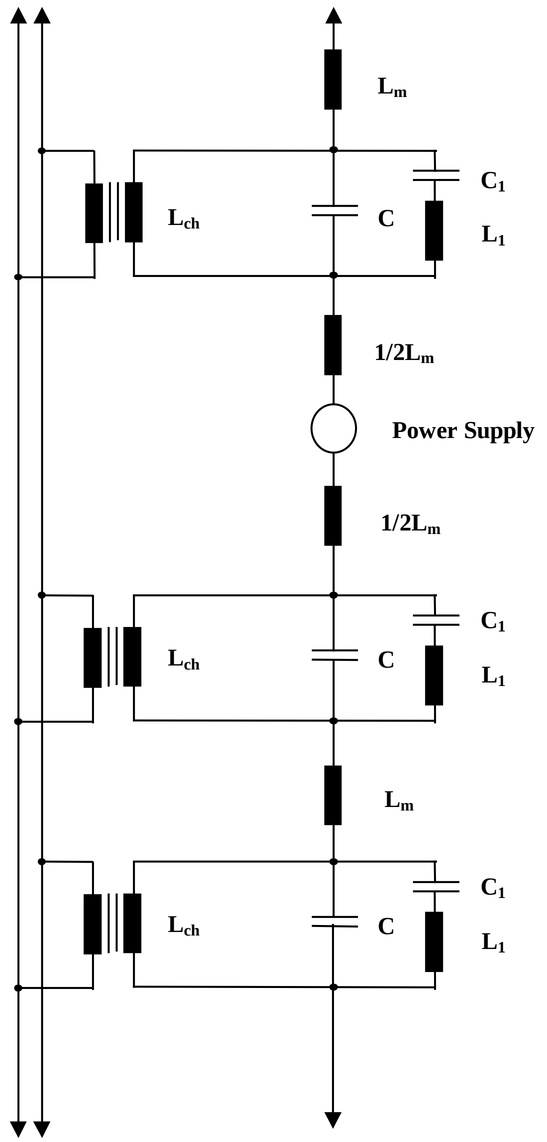

Figure 7.1. Dipole/Quadrupole Power Supply Resonant System Diagram

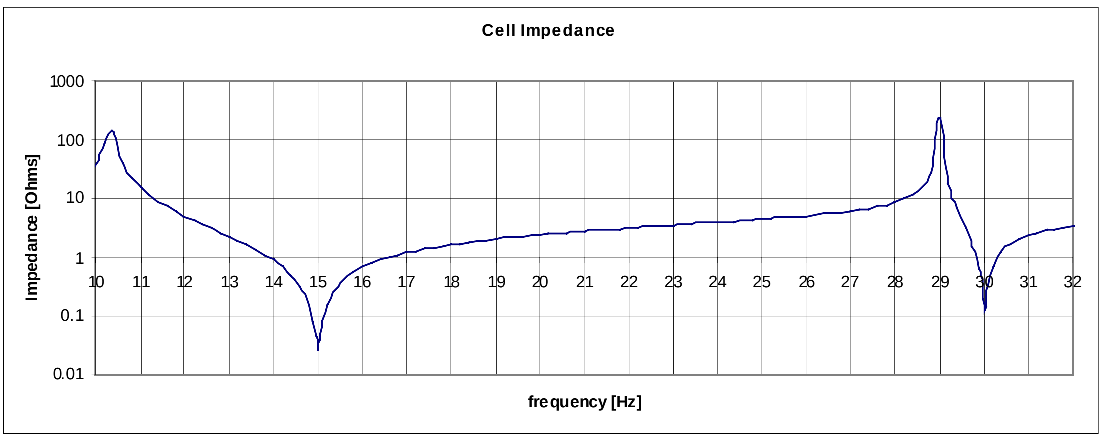

Figure 7.2. Resonant Cell Frequency Response

Although, owing to its series connection, the distributed resonance circuit provides a basic uniformity in magnet currents, the effect of leakage capacitance currents to ground can distort this current equality to a degree that is significant. Since these leakage paths are distributed around the network in a generally uniform manner, it is necessary to ensure that the a.c. potentials of the corresponding points in the network attain a similar value. This is achieved by matching equivalent cell magnet inductances, requiring close tolerances of each resonant cell component and having auxiliary windings in chokes L_{ch} connected in parallel with each other.

7.2.3. System Parameters

Calculations of d.c. resistances and d.c. losses have been done using the proposed stranded conductor described in Chapter 6; a.c. resistances and a.c. losses have been scaled from the Fermilab Booster. All system parameters will be verified when a prototype resonant cell becomes available. System parameters are listed in Table 7.2.

Table 7.2. System Parameters

	Stage 1 12 GeV Operation	Stage 2 16 GeV Operation
I_{rms}	3,018 A	3,955 A
Total a.c. induced voltage, peak	246,960 V	323,776 V
Total d.c. voltage	1,450 V	1,900 V
Number of resonant cells	30	30
Voltage to ground, peak	4,358 V	5,713 V
Total a.c. losses	1.10 MW	1.90 MW
Total d.c. losses	1.85 MW	3.17 MW
Beam pipe losses	1.10 MW	1.97 MW
Total losses	4.05 MW	8.87 MW
Number of power supplies	3	3
Power supply current, peak	4,900 A	6,400 A
Power supply voltage, peak[1]	±900 V	±1,200 V

7.2.4. 16 GeV Upgrade

The resonant cell chokes and capacitor banks are designed for full utilization when the system is upgraded to 16 GeV. Adding capacitor units and fuses to an upgrade-ready frame (Figure 7.3) increases the rating of the capacitor banks while maintaining their net capacitance.

[1] Includes 30% margin for off-resonant operation

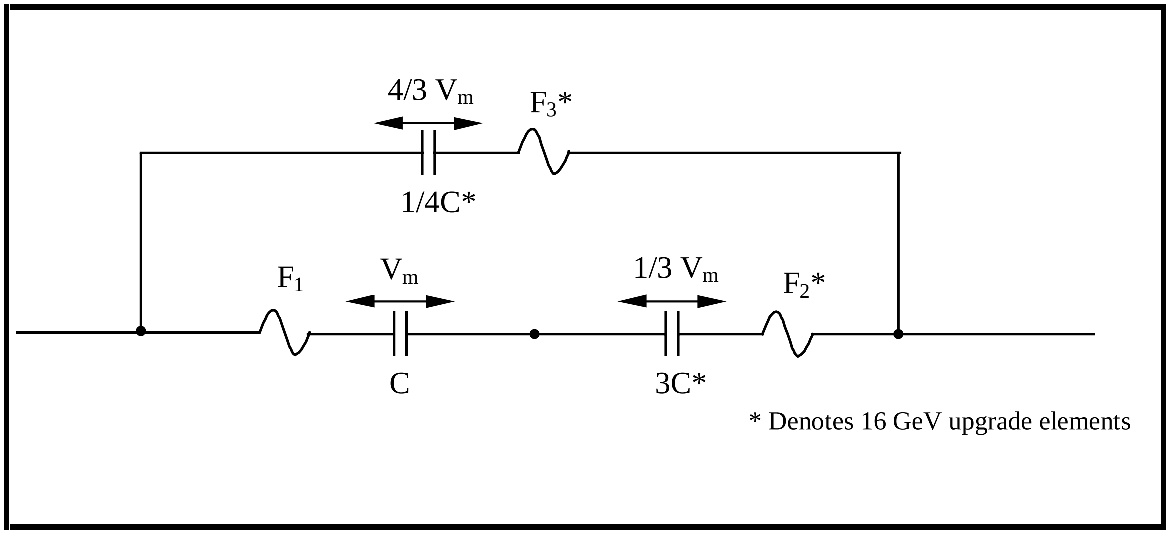

Figure 7.3. Cell Capacitor Banks Upgrade

Chokes will require a two-step upgrade. First, 12 GeV chokes are reconfigured to handle 33% higher peak current and then additional units are added in series (Figure 7.4) to arrive at the required total inductance. The 12 GeV/16 GeV convertible chokes will have multiple main and auxiliary current terminals.

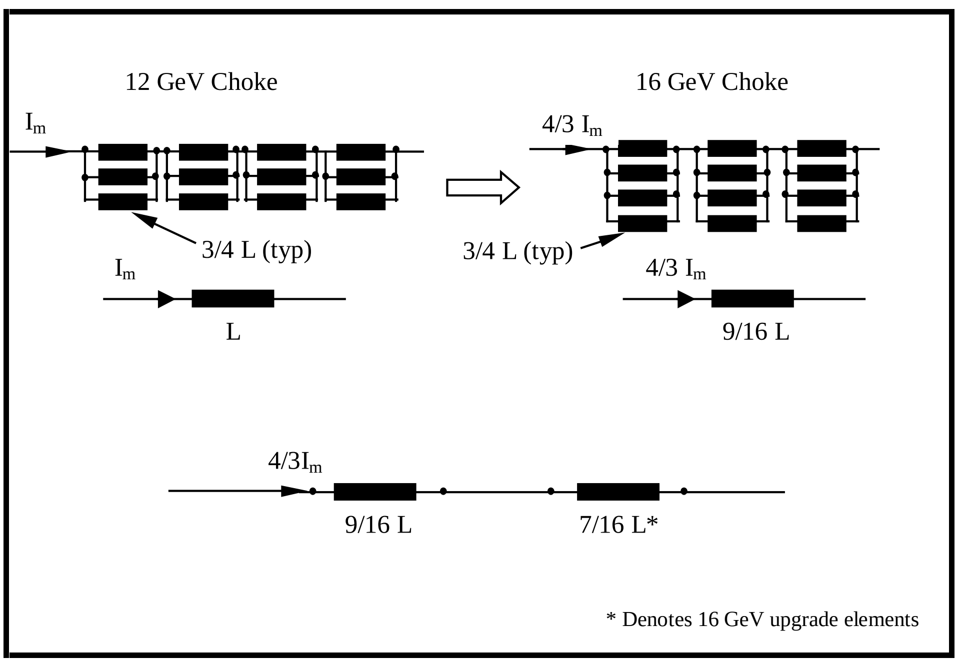

Figure 7.4. Two Step Cell Chokes Upgrade

7.3. Quadrupole Tracking and Correction Power Supply

7.3.1. System Requirements

The system peak current requirement at given frequencies is set by the required tune compensation or tracking compensation, whichever is higher. It is assumed that only frequencies up to the 7^{th} harmonic (105 Hz) will be required to provide sufficient quadrupole field gradient correction (tracking compensation and tune control). System requirements are listed in Table 7.3.

Table 7.3. System Requirements

Frequency [Hz]	Tracking Compensation [± %]	Tune Control [± %]	Power Supply Peak Current Requirement [± %]
15	0.53	2.00	2.00
30	0.36	0.20	0.36
45	0.21	0.10	0.21
60	0.09	0.10	0.10
75	0.02	0.10	0.10
90	0.03	0.10	0.10
105	0.03	0.10	0.10

7.3.2. System Design

Driving the quadrupole trim coils with currents specified in Table 7.3 provides the quadrupole field gradient correction. A bucking choke is used for each quadrupole circuit to cancel the voltage induced in the trim coil circuit caused by the main coil circuit. The estimated peak induced voltage is 8.5 kV per quadrupole family.

The primary windings of the bucking choke are connected in series with the quadrupole trim windings, while the secondary windings are connected in series with the main coils. The mutual inductance of the bucking choke must be equal in value (but opposite in sign) to the sum of mutual inductances of the quadrupole main/trim coil transformers for proper operation.

Figure 7.5 shows the principle of the system and Table 7.4 lists the system requirements.

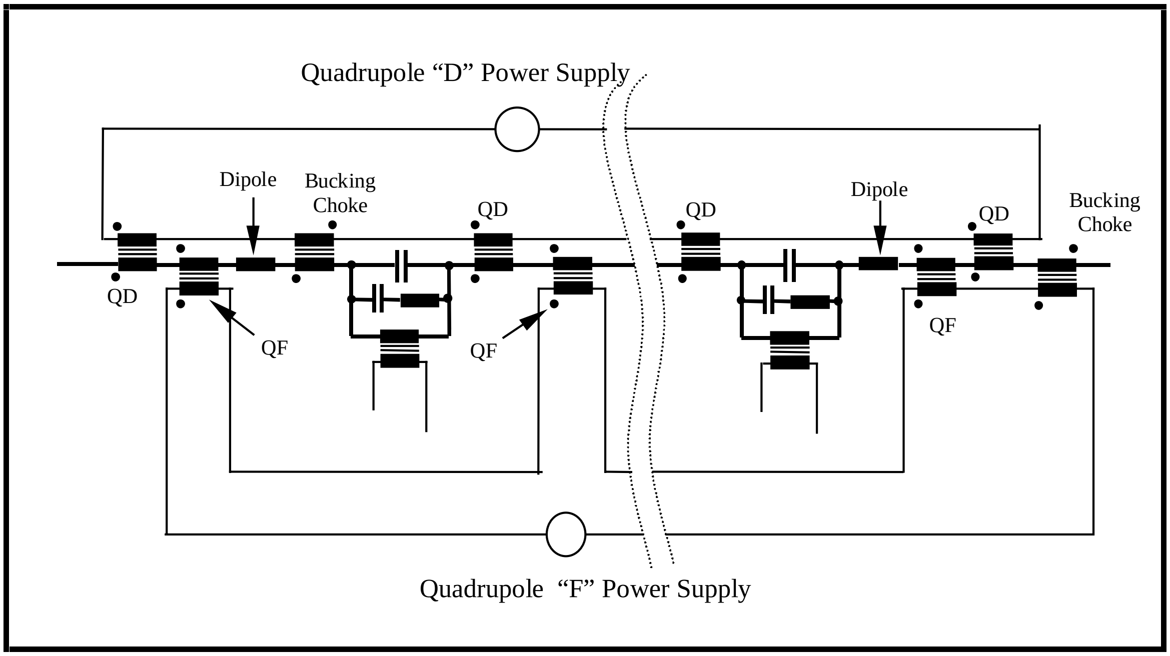

Figure 7.5. The Principle of the Quadrupole Correction System

Table 7.4. System Parameters

	12 GeV Operation	16 GeV Operation
Number of quadrupole "D" trim circuits	6	6
Number of quadrupole "F" trim circuits	6	6
Number of bucking chokes per trim circuit	1	1
Quadrupole "D" main coil inductance, per circuit total	16.33 mH	16.33 mH
Quadrupole "F" main coil inductance, per circuit total	16.33 mH	16.33 mH
Quadrupole main number of turns per pole (electrical equivalent)	4	4
Quadrupole trim number of turns per pole (electrical equivalent)	1	1
Quadrupole main-trim coil coupling coefficient	0.98	0.98
Number of bucking chokes	12	12
Bucking choke main coil inductance	3.77 mH	3.77 mH
Bucking choke turns ratio (trim coil : main coil)	25 : 27	25 : 27
Bucking choke peak stored energy	71 kJ	94 kJ
Bucking choke main-trim coil coupling coefficient	0.98	0.98
Power supply peak current	±544 A	±725 A
Power supply peak voltage	±530 V	±706 V
Trim circuit rms current	492 A	520 A
Power supply minimum bandwidth	210 Hz	210 Hz
Total number of power supplies	12	12

7.4. Horizontal Dipole Correction Power Supply

Figure 7.6 shows the required current waveform and Table 7.5 lists the system requirements.

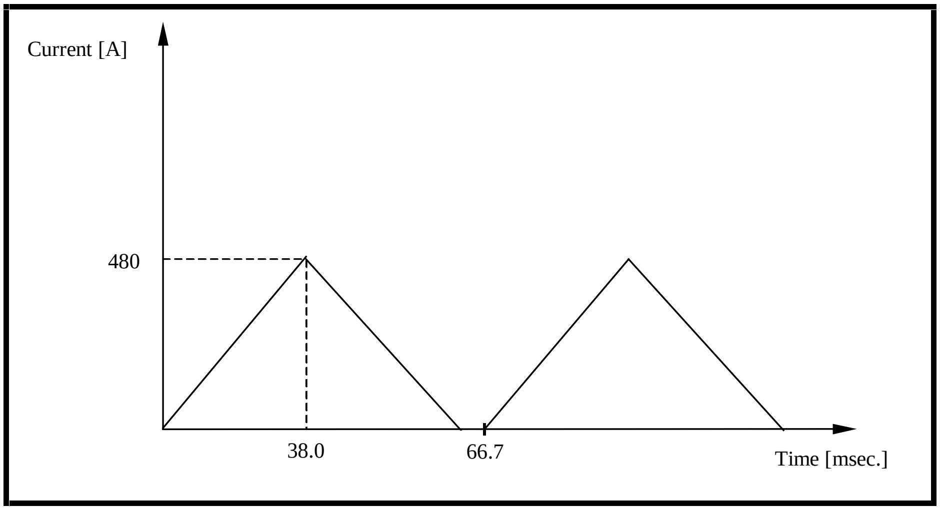

Figure 7.6. Horizontal trim required current waveform

Table 7.5. System Requirements

Parameter	12 GeV Operation	16 GeV Operation
Repetition Rate	15 Hz	15 Hz
Max. Current, I_{max}	480 A	480 A
Required current waveform	Figure 7.6	Figure 7.6
$\Delta I / I_{max}$	0.01%	0.01%
Number of turns per pole	6	6
Long Dipole Trim Coil Inductance	3.8 mH	3.8 mH
Number of Long Dipoles	36	36
Short Dipole Trim Coil Inductance	2.8 mH	2.8 mH
Number of Short Dipoles	12	12

The system is designed so that horizontal orbit correction is accomplished using trim coils wound on the dipole magnet cores. Each dipole magnet is supplied with two sets of trim coils having an equal number of turns. They are connected in series but with opposite magnetic sense so that no net voltage is induced across them by the main coil current. The common connection point between the two trim coils is then connected together with the common points between the other trim coils as shown in Figure 7.6. Each trim set is driven by an independent programmable power supply. The effect of energizing a single trim set is to cause a local horizontal orbit shift without altering the beam orbit path length and beam energy.

System parameters are shown in Table 7.6 and the principle by which the horizontal correction system works is shown in Figure 7.7.

Table 7.6. System Parameters

Parameter	12 GeV Operation	16 GeV Operation
I_{rms}	210 A	280 A
Number of Power Supplies	48	48
Power Supply Current, peak	360 A	480 A
Power Supply Voltage, peak	±40 V	±50 V

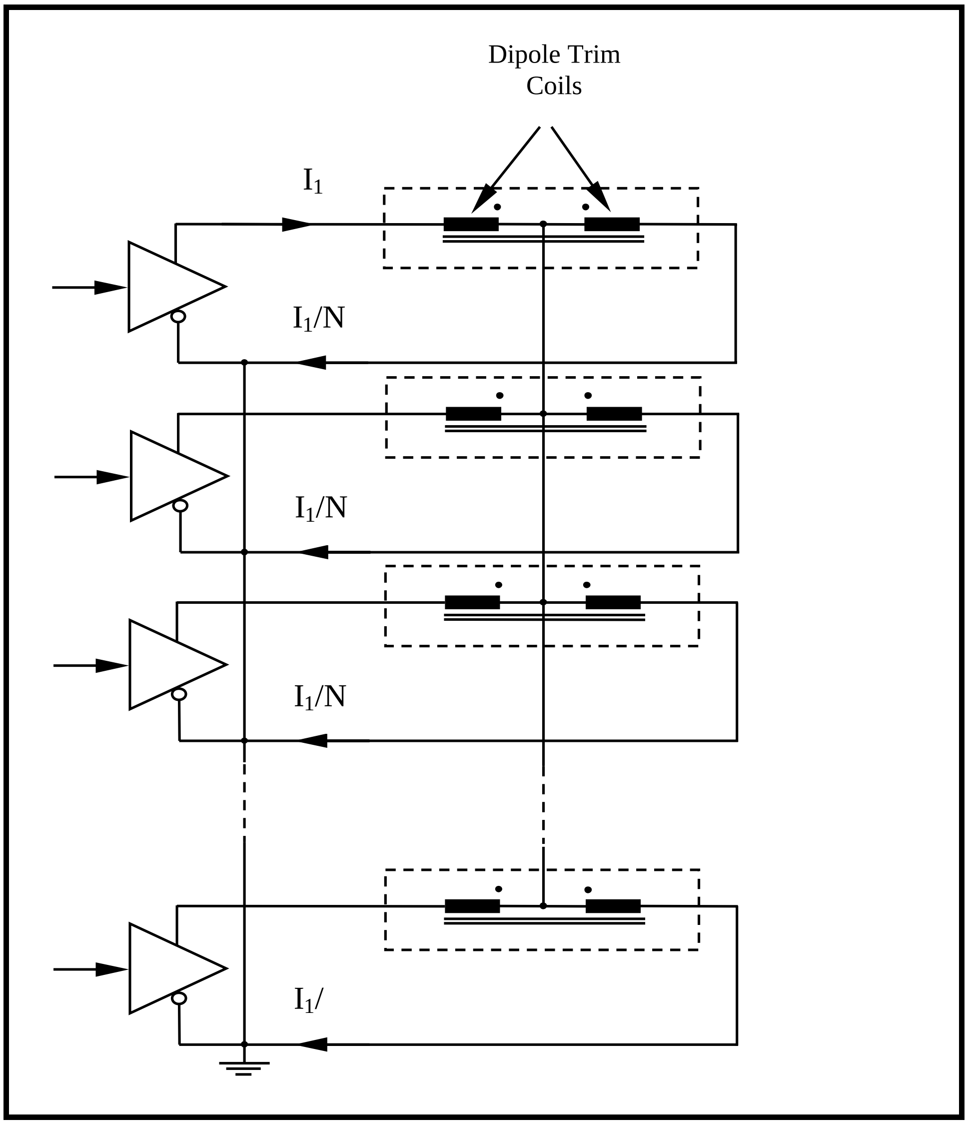

Figure 7.7. Horizontal Dipole Correction Power Supply System Principle

7.5. Vertical Dipole Correction Power Supply

7.5.1. System Requirements

The required waveform for the vertical correction system is shown in Figure 7.8 and the system requirements are listed in Table 7.7.

Figure 7.8. Vertical trim required current waveform

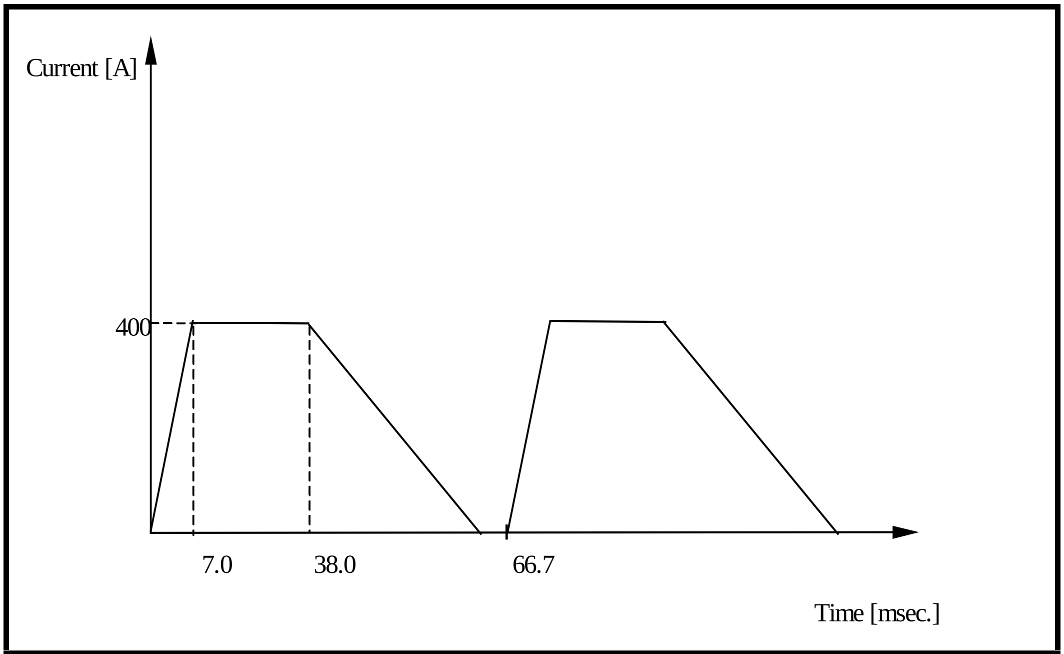

Table 7.7. System Requirements

Parameter	12 GeV Operation	16 GeV Operation
Repetition Rate	15 Hz	15 Hz
Max. current, I_{max}	300 A	400 A
Required current waveform	Figure 7.8	Figure 7.8
$\Delta I / I_{max}$	0.01%	0.01%
Dipole Trim Coil Inductance	10 mH	10 mH
Number of Vertical Trim Dipoles	36	36

7.5.2. System Design

Separate corrector magnets situated at specific points in the ring accomplish vertical orbit correction. The vertical corrector magnets are driven with programmable power supplies similar to those used for horizontal correction. Parameters are shown in Table 7.8.

Table 7.8. System Parameters

Parameter	12 GeV Operation	16 GeV Operation
I_{rms}	230 A	310 A
Number of Power Supplies	36	36
Power Supply Rated Current, peak	300 A	400 A
Power Supply Rated Voltage, peak	±450 V	±600 V

7.6. Sextupole Power Supply

The sextupole power supply system consists of 3 independent circuits with distributed power supplies: SF loop, SD loop, and a stray field compensation loop. System requirements are in Table 7.9 and system parameters in Table 7.10.

Table 7.9. System Requirements

Parameter	12 GeV Operation		16 GeV Operation	
Repetition rate	15 Hz		15 Hz	
Sextupole specific inductance	2.45 mH/m		2.45 mH/m	
$\Delta I/ I_{max}$	0.01%		0.01%	
Magnet type	SF	SD	SF	SD
Max. magnet current, I_{max}	1350 A	1,965 A	1800 A	2,620 A
Min. magnet current, I_{min}	76 A	128 A	101 A	147 A
I_{dc}	713 A	1038 A	950 A	1,383 A
I_{ac} (15 Hz)	637 A	928 A	850 A	1,237 A
0.125 I_{ac} (30 Hz)	80 A	116 A	106 A	155 A
Number of sextupoles	24	24	24	24
Total length of sextupoles	7.2 m	7.2 m	7.2 m	7.2 m
Total inductance of sextupoles	17.64 mH	17.64 mH	17.64 mH	17.64 mH

Table 7.10. System Parameters

Parameter	12 GeV Operation			16 GeV Operation		
Circuit	SF	SD	Comp.	SF	SD	Comp.
Number of sextupoles per circuit	24	24		24	24	
I_{rms}	960 A	1,397 A	440 A	1,279 A	1,862 A	590 A
Induced voltage per circuit, peak	1,325 V	1,929 V	25 V	1,766 V	2,572 V	33 V
Number of power supplies	2	3	1	2	3	1
Power supply current, peak	1,800 A	2,700 A	900 A	1,800 A	2,700 A	900 A
Power supply voltage, peak	±700 V	±700 V	±30 V	±1,000 V	±1,000 V	±40 V

7.7. Power Distribution System

The existing site power distribution system is not able to meet the Proton Driver power demand. Therefore, as part of the Proton Driver Project, infrastructure upgrades will be needed. To meet the power requirements, a new substation will be installed. This will be utilized together with existing facilities. Table 7.11 gives power requirements and Figure 7.9 shows single line diagram of the power distribution system. To take advantage of the existing 345 kV equipment, the substation will be located inside Kautz Road Substation.

Table 7.11. Power distribution system requirements

Subsysem	RF system	Main PS	Sext. PS	Quad PS	Vertical corrector	Horiz. corrector	Vacuum system	Conv. power	Total
Peak MVA	40.0	18.0	11.7	5.0	10.0	0.8	1.8[2]	1.5	88.8
RMS MVA	10.0	16.1	8.5	4.4	8.9	0.7	1.8	1.5	51.9

7.8. Required R&D

The power supply system will require a substantial R&D program. Major efforts will be directed towards:

- Design and testing of high voltage magnets (dipole and quadrupole)
- Prototyping a complete resonant cell. This will include dipole and quadrupole prototypes, chokes, capacitors, power supply, regulation and control systems.
- Developing a quadrupole tracking system. This will include a prototype of a resonant cell, bucking choke, tracking power supply, regulation, and control systems.
- Development of the main dipole/quadrupole power supplies employing the newest IGBT technology.

[2] May increase to 4.0 MVA during magnet bake-out.

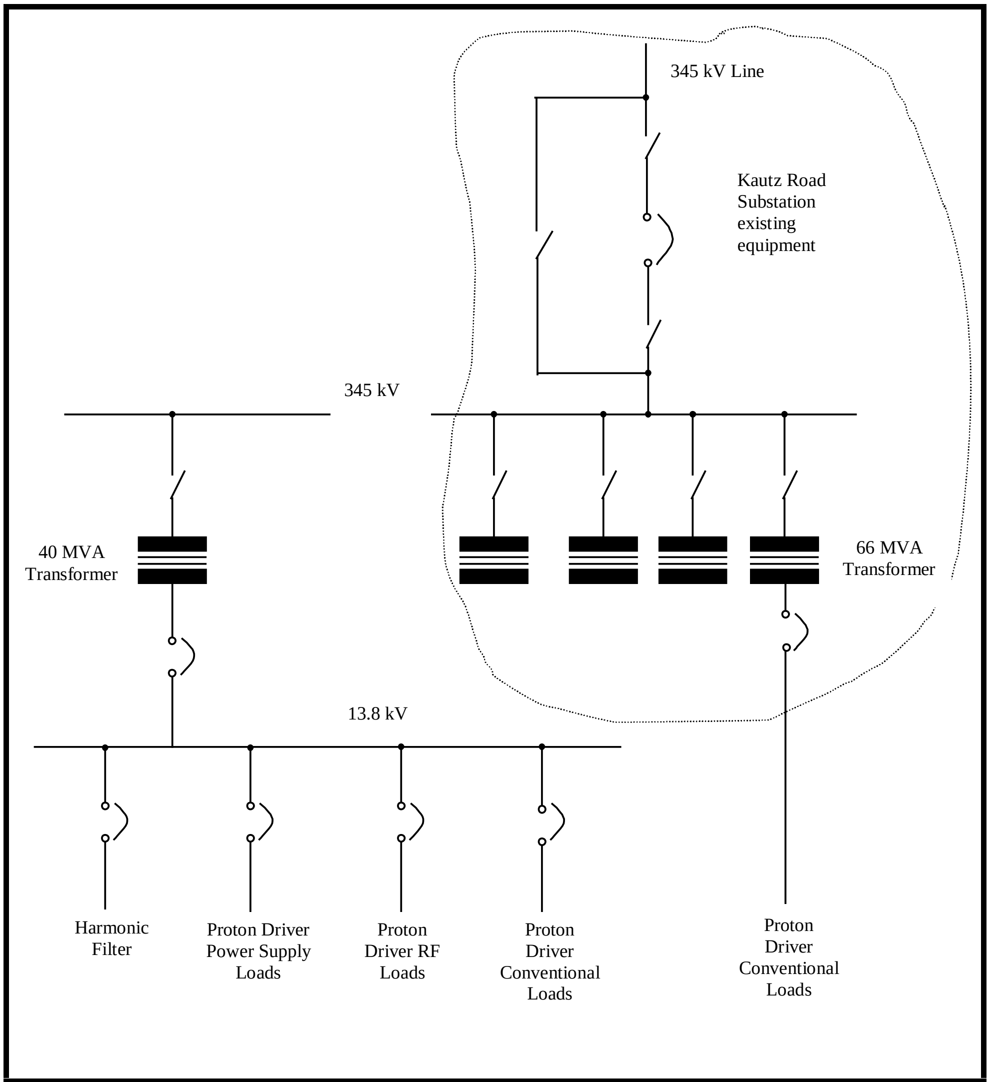

Figure 7.9. Power Distribution System Diagram

References

[1] FERMILAB-Pub-74/85 0323.000 (1974)

[2] R. Hettel, C. Jach, - "The 10 Hz Resonant Magnet Power Supply for the SSRL 3 GeV Injector," 1991 IEEE Particle Accelerator Conference.

[3] C. Jach, A. Medvedko, Y. Fishler – "Energy Storage Inductor for the Low Energy Booster Resonant Power Supply System," 1993 IEEE Particle Accelerator Conference.