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# FERMILAB BOOSTER CORRECTION ELEMENTS UPGRADE

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Abstract The Fermilab Booster Correction Element Power Supply System is being upgraded to provide significant improvements in performance and versatility. At the same time these improvements will compliment raising the Booster injection energy from 200 MeV to 400 MeV and will allow increased range of adjustment to tune, chromaticity, closed orbit and harmonic corrections. All correction elements will be capable of ramping to give dynamic orbit, tune and chromaticity control throughout the acceleration cycle. The power supplies are commercial switch mode current sources capable of operating in all four current-voltage quadrants. External secondary feedback loops on the amplifiers have extended the small signal bandwidth to 3 kHz and allow current ramps in excess of 1000 A/sec. Implementation and present status of the upgrade project is described in this paper.

## INTRODUCTION

The Fermilab Booster Accelerator is a fast cycling combined function proton synchrotron.[1] Injection energy is currently 200 MeV and extraction energy is 8 GeV. The magnet excitation is a biased 15 Hz sinusoid derived from a resonant power supply system. The lattice structure is broken up into twenty four identical periods. Each period consists of a 6 meter long straight section, 4 3-meter gradient magnets and a 1.2 meter short straight section which separates pairs of gradient magnets. (Figure 1) Each straight section (both long and short) contains a correction element package consisting of a horizontal and vertical dipole and a normal and skew quadrupole. In

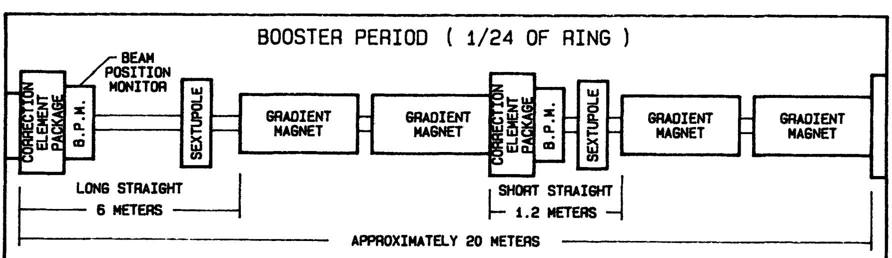


Figure 1

*Operated by the Universities Research Association under contract with the U.S. Department of Energy.

addition half of the short straights contain horizontal sextupole magnets and three of the long straights contain vertical sextupole magnets. These sets of magnets provide injection orbit correction and control, tune control, harmonic correction control and chromaticity control for the Booster. All correction magnets are air core devices to allow fast ramping and in the case of the dipole and quadrupoles are nested concentrically around the beam pipe to conserve space. Table I lists correction element parameters.

TABLE I Correction element parameters

| | Horizontal Dipole | Vertical Dipole | Normal Quadrupole | Skew Quadrupole | Vertical Sextupole | Horizontal Sextupole |
|---|---|---|---|---|---|---|
| Length (in) | 12.75 | 12.75 | 12.75 | 12.75 | 16.75 | 13 |
| Resistance (ohms) | 4.4 | 2.5 | 14 | 10.5 | 1.5 | .6 |
| Inductance (mH) | 130 | 97 | 60 | 19 | 10.3 | 1.3 |
| Current Max (amps) | 10 | 10 | 2 | 2 | 90 | 90 |
| Number of magnets | 48 | 48 | 48 | 48 | 9 | 12 |
| Strength/Amp ($\int B\cdot l$ or $\int B'\cdot dl$ or $\int B''\cdot dl$) | 926 g-cm | 1293 g-cm | 220g | 88g | ---- | 37 g/m |

## UPGRADE MOTIVATION

The motivation for upgrading the correction element system is two fold. First the old system of power supplies and controls has a number of limitations that are related to the systems' age and original design specifications.

The dipole supplies were designed for DC operation and are voltage limited so as not to allow ramping. In addition polarity control was via a relay type reversing switch further limiting possible ramp applications. The present supplies also limit three element bumps to span three periods encompassing either three long straights or three short straights. Furthermore output device limitations on the dipole supplies prevent half the correction dipoles from being able to give full aperture orbit bump tuning range at the lower $\beta$ points in the ring even at the injection energy. It is desirable to upgrade the supplies to accomplish a "narrow" orbit bump consisting of a long-short-long or short-long-short elements spanning only one period.

The quadrupole supplies while capable of ramping are bandwidth limited to approximately 1 kHz and similarly voltage limited. Skew quadrupoles are run DC and used for decoupling horizontal and vertical betatron motion at injection. The two families of quadrupoles (long straight/short straight) allow a change of tune of ±.6 units in either plane at injection but provide only limited control at 8 GeV. Since both quad and skews are individually adjustable they also provide for harmonic correction as well.

The old sextupole power supplies were designed to operate in only one voltage/current quadrant and are bandwidth limited to a few hundred Hertz.

The second motivation for upgrading the correction element system is a planned increase of the Booster injection energy to 400 MeV. Currently the Booster beam intensity is space charge limited to 3-$4\times10^{10}$ protons per bunch. Increasing the Linac energy and Booster injection energy to 400 MeV, thus raising the space charge limit, is part of the Tevatron luminosity upgrade scheduled over the next several years.[2] In order to accommodate the change in Booster energy and improve the correction element performance, the system is being re-worked at this time. Design goals for the improvements include:

1. Increase bandwidth of ramped quadrupole and sextupole supplies (including high power bandwidth).
2. Increase range of tune control at high energy end of cycle.
3. Provide four quadrant power supplies for all correction elements for ramping.
4. Increase range of orbit bump dipoles to provide full aperture bumps at injection everywhere in the ring.
5. Be able to do orbit bumps that span only one period of the ring("narrow" bumps).
6. Be able to ramp dipoles to provide some high field orbit correction.
7. Be able to ramp skew quadrupoles.

## IMPLEMENTATION

A commercial switch mode current source capable of operating in all four voltage/current quadrants was chosen to drive each load. This decision was based on price, versatility, engineering time, and power dissipation considerations. The amplifiers selected were Copley Controls models 220 and 230 servo amplifiers.[3] The evolution of switch technology, using MOSFET's to higher frequencies, allows development of amplifiers that approach linear amplifier type response over the frequency range of interest in this application. The switch frequency for both models is 71 KHz. The dual bridge configuration of the amplifier gives four quadrant operation using a single unipolar DC bulk supply. In addition, power dissipation in the amplifier can be as low as 90 watts while delivering up to 1.5 kw to the load. This provides for efficient packaging allowing the nearly 200 channels of correction element power supplies to be installed in eight relay racks.

The model 220 amplifiers are operated at 80 V DC from the bulk supply. They are capable of 10 amperes continuous current and peaks of 22 amperes. All dipoles, quadrupoles and skew quadrupoles will be powered with this model. The amplifier is inheritantly stable with all these loads but due to frequency roll-off in the response of the amplifiers, caused by the loads, a secondary current feedback loop tailored to each type of load has been added to compensate and extend the bandwidth. A low cost current transductor has been added to accomplish this.[4] Small signal bandwidth for both types or quadrupoles has been extended to 3 kHz. Dipole bandwidth is extended to 1.2 kHz. Full power di/dt of 300A/sec is possible for the dipoles and 1000 A/sec for the quadrupoles. This allows the dipoles to ramp to full output over the 35 msec acceleration cycle and allow full range of tune control to be accomplished in 2 msec.

The two sextupole power supplies use the model 230 amplifier. These units use a 150 volt DC bulk power supply. The six amplifiers in each supply are configured as one master and five slaves all operating in parallel giving a peak output current capability of 90 amperes and a continuous current of 60 amperes. Sextupole power supply bandwidth is about 3 KHz and full power di/dt exceeds 4500 A/sec. Each sextupole power supply occupies a single relay rack. The magnets for each type of sextupole are driven in series. Figure 2 is a photograph of one of the two sextupole supplies showing the six paralleled amplifiers and the power supply controller.

Power supply protection is broken into two parts. Each amplifier has internal over voltage, over current and thermal protection built in and is fused for fault isolation from the bulk supply. In addition several levels of interlocks protect the load and system as a whole. Cooling flow and temperature interlocks protect the amplifier and bulk supply independent of the amplifier internal protection. RMS current protection for each load is provided by a microcomputer in the power supply controller. A tracking error alarm is provided to indicate output in compliance with the reference signal for each load. The power supply controller provides monitoring and control for 24 amplifiers and is interfaced to the CAMAC based Booster control system. Reference waveforms are generated by CAMAC control cards.

## OTHER CONSIDERATIONS

At Fermilab, this was the first use of switch mode power supplies for accelerator devices. There was some initial fear that the 71 KHz switching frequency might somehow generate noise that could disturb other sensitive accelerator systems. To help allay these fears, when new cabling for the correction elements was installed a shielded multiconductor cable was used for the dipoles and two types of quadrupoles. However, the sextupoles used the existing unshielded cable and no noise problem have been identified with the new supplies.

Upgrades to the Fermilab Main Ring correction element system are also in progress. This system has chosen to use linear power operational amplifiers in its upgrade, primarily to avoid using high frequency switch mode supplies. The upgrade to the Main Ring correction elements has provided an opportunity for comparison with the switch mode supplies. While the comparison is not complete, at least on a cost basis the two systems are favorably matched. Both upgrades cost between one to two thousand dollars per channel to implement.

## SUMMARY

Currently two sextupole power supplies are operational. Dipoles and quadrupoles are expected to be completed within the next year. There have been no problems encountered with the switch mode amplifiers to date. The switchers have provided a economical and reliable alternative to linear amplifiers for this application. All design goals listed earlier have been met.

## REFERENCES

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3. Copley Controls Corp.; 375 Elliot St., Newton, Mass.
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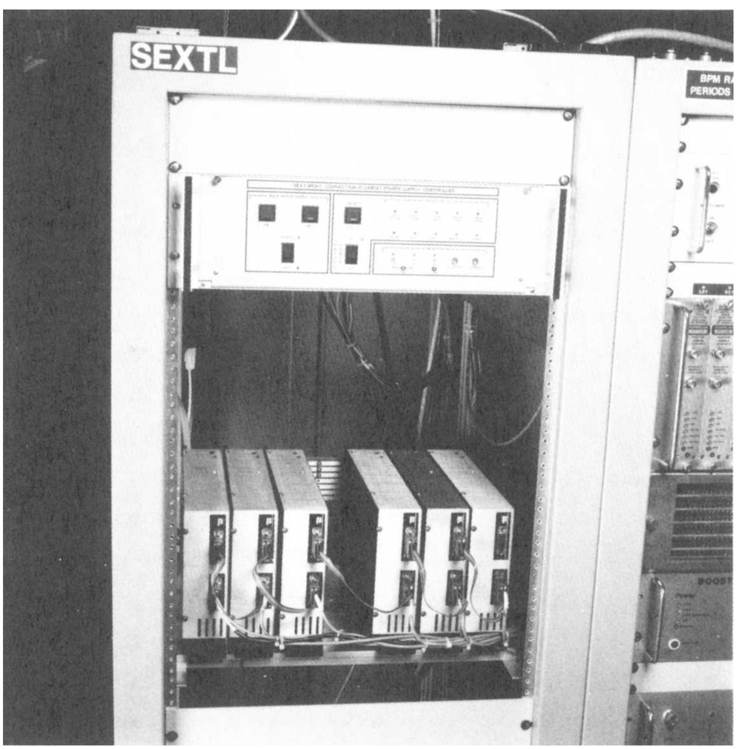


Figure 2 Typical Sextupole Power Supply