COMBINED PANOFSKY QUADRUPOLE & CORRECTOR DIPOLE *

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Abstract

Two styles of Panofsky Quadrupoles with integral corrector dipole windings are in use in the electron beam line of the Free Electron Laser at Jefferson Lab. We combined steering and focusing functions into single magnets, adding hundreds of Gauss-cm dipole corrector capability to existing quadrupoles because space is at a premium along the beam line. Superposing a one part in 100 dipole corrector field on a 1 part in 1000, weak (600 to 1000 Gauss) quadrupole is possible because the parallel slab iron yoke of the Panofsky Quadrupole acts as a window frame style dipole yoke. The dipole field is formed when two electrically floating "current sources", designed and made at JLab, add and subtract current from the two opposite quadrupole current sheet windings parallel to the dipole field direction. The current sources also drive auxiliary coils at the yoke's inner corners that improve the dipole field. Magnet measurements yielded the control system field maps that characterize the two types of fields. Field analysis using TOSCA, construction and wiring details, magnet measurements and reference for the current source are presented.

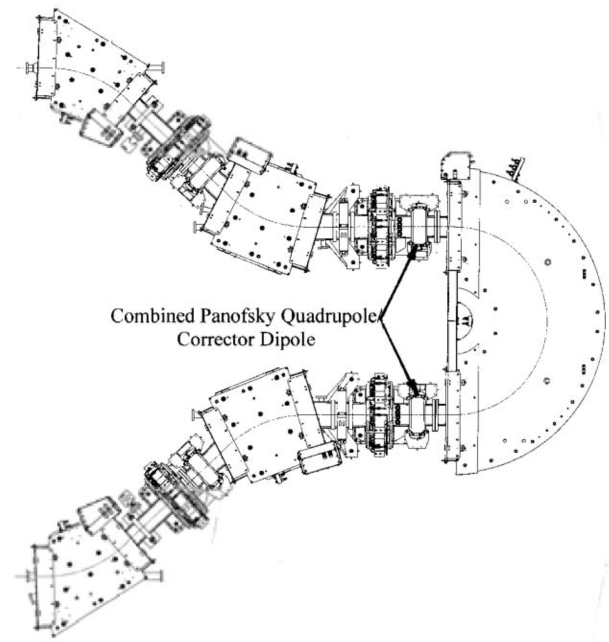

Figure 1: Arc 2, Showing Combined Magnets.

INTRODUCTION

Seventy-two small dipole correctors (predominantly 1000 Gauss-cm) are used throughout the electron beam transport system for the 10 KW Upgraded FEL [1, 2] at the Thomas Jefferson National Accelerator Facility. In most instances, this function is performed by a pair of nesting, saddle shaped, air core windings. Where space along the beam line is limited, five correctors are made by superposing the dipole corrector into the body of a Panofsky Quadrupole [3] forming combined function magnets. Four installations form 1000 Gauss-cm correctors, bending the electron beam vertically in the parallel beam paths on either side of the 180° bends in the Energy Recovering Linac's two Arcs. The base Panofsky Quadrupole for these positions is rated at a gradient integral up to 1000 Gauss. See Figure 1 for a view of Arc 2. The fifth position for a combined magnet is in the injector beam line, a 300 Gauss–cm vertical correction dipole is combined with a 600 Gauss quadrupole.

THE FOUR ARC CORRECTORS

We first consider the four combined magnets in the Arcs. The Upgrade FEL Beam Line Design [4] left no room for vertical correctors in these locations. The beam at those locations is the widest in the machine: 15 cm wide and 0.5 cm high (with a correspondingly wide vacuum chamber). The required field direction is horizontal for vertical beam deflection.

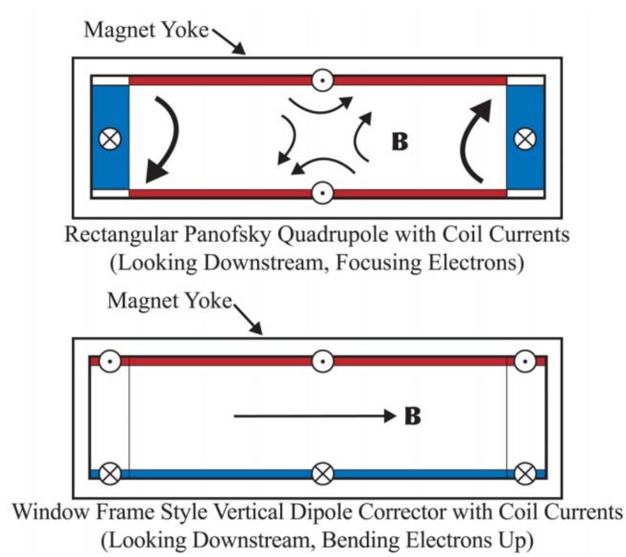

Figure 2: Quadrupole and Dipole Current Flows.

We had the inspiration that we could combine the vertical corrector function with the rectangular Panofsky Quadrupoles already planned for this region. These Quadrupoles are relatively weak, are built "flattened" with no compromise to their field gradient

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uniformity and have a window frame-like yoke that, at full quadrupole current, is not near saturation.

Superposition of a dipole onto the Panofsky Quadrupole adds current to one of the four coils and subtracts it from its opposing coil. We added variable current coils to the vacant corners of the Panofsky design. The latter coils fulfill the need, in a window frame dipole, to have continuous current sheets next to the two return legs from pole tip to pole tip. See Figure 2. The Panofsky Quadrupole's 2D finite element was modeled in TOSCA. We added superposed currents in the top and bottom coil and the corner currents as well to create a superposed horizontal dipole field. The model indicated we would be successful with this superposition method. Our model was in 2D only because of time/resource limitations.

The above analysis did find that by raising the current density in the corner blocks above the density in the top/bottom coils, our model improved to achieve the specified 1 part in 100 corrector dipole field quality over the required 20 cm wide x 5 cm good field region.

Concept Implementation

Several obstacles arise when superposing dipole current onto quadrupole windings. First, conventional voltage regulated, grounded power supplies can't be used to create the superposed current. As the quadrupole is set to different values, the leads on its coils exhibit a variable EMF. The superposed corrector dipole's power supplies, if they are voltage regulated, will therefore not force the

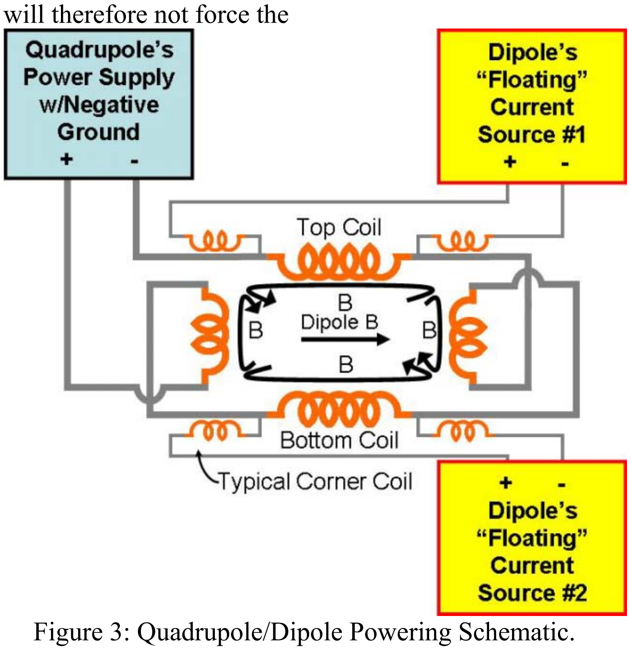

Figure 3: Quadrupole/Dipole Powering Schematic.

constant current required. Fortunately, a class of power supplies known as a "Current Source" is available. A Current Source drives a set current regardless of the voltage seen by its output leads. For our tests and some operations we used Kepko, BOP Series, 4-quadrant supplies set to "regulate on current".

The second obstacle is that no configuration of the connections from only one current source for the dipole can simultaneously power the opposing coils described above. This conundrum is clarified by observing the schematic of Figure 3. As an illustration, assume the first dipole current source adds current to one lead of the top coil and withdraws the current from its other lead. To use this same current in the bottom coil the output current from the top coil has to continue in series, inserting at the opposing lead of the bottom coil. The current is then drawn out from the bottom coil's output connection. The problem is that this output lead short circuits to the input lead of the top coil through a side coil. No topology of connections overcomes this problem.

Two current sources solves the problem, but only if the sources are electrically floating, independent of one another. With independence, the short circuit becomes irrelevant. Both current sources must supply identical current at the 1 part in 1000 level to maintain the required field quality of the two systems. Neither lead of these sources can be grounded because grounding provides an unacceptable alternate circuit through the quadrupole coil's ground.

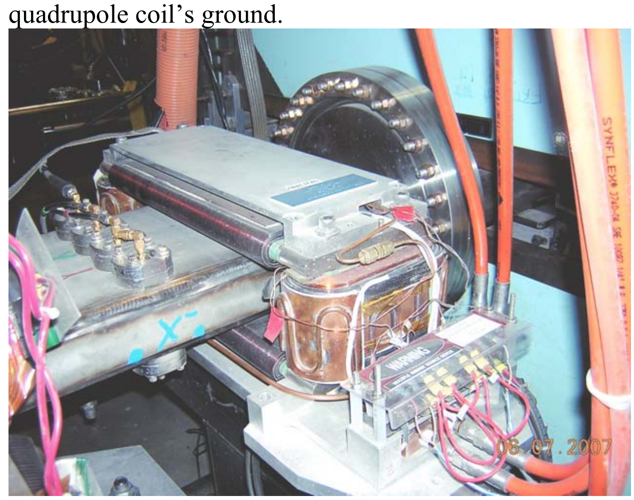

Figure 4: Combined Magnet in Arc Showing Corner Coils.

Instead of continuing computer analysis, we tested our concept on the subject quadrupoles that were already on hand. We added a set of prototype corner coils. We applied the superposed current to the upper and lower coils using 2 Kepko Current Sources isolated from ground. For our magnetic measurements, we powered all four of the prototype, add-on, corner-current coils in series with an additional power supply. This feature allowed us to experimentally determine the required current density in the corner coils with respect to the density in the top and bottom coils. As seen in the schematic of Figure 3, in service, we powered two of these corner current blocks from each Current Source to subject them to identical loads

Test Results

We found that, over the required "good field' region, the uniform dipole field integral could be obtained with

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adjustment of the current in the corner coils to about 145% of the current density in the main coils. We found that the required current in both quadrupole coils and corner coils is linear with dipole field and that the 1 part in 1000 quality and strength of the quadrupole field was unaffected by superposing the dipole fields for all field orientations. Our method of setting fields in these magnets is to run the quadrupole through its hysteresis loop followed by setting it to the current generating the required gradient integral (as a focusing or defocusing quadrupole). We found that after setting the quadrupole, the dipole field integral (also in either field direction) could be predictably set by dialing up the appropriate and identical current in both Current Sources.

Implementation in the Beam Line

After testing, we wound "production" corner coils with the number of turns necessary to match the current density ratio (between corner and top/bottom coils) established in our test. These coil systems were retrofitted into the Panofsky Quadrupoles destined for the four positions requiring the added vertical corrector dipole. Figure 4 shows a typical installation.

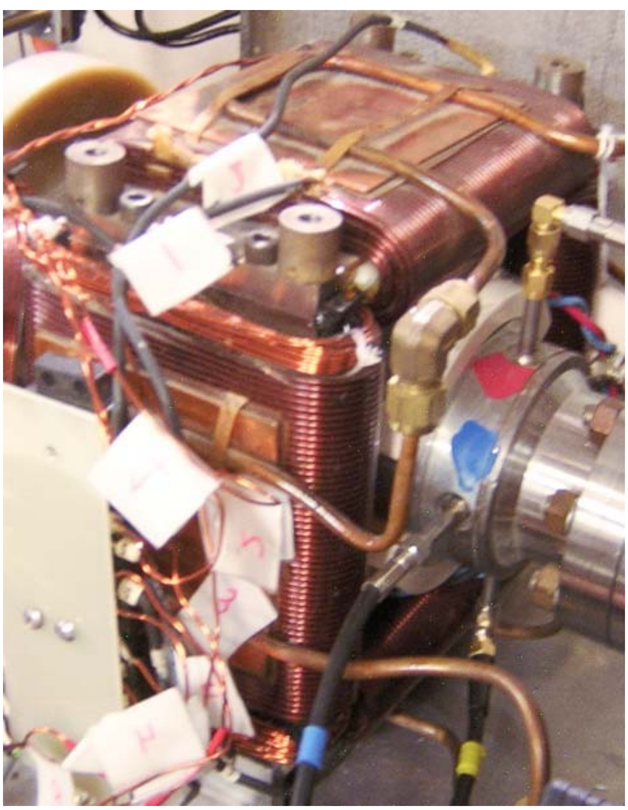

Figure 5: Combined Quadrupole/ Dipole in Injector.

Our EPICS Control System couldn't control the Kepko Current Sources. With the great cooperation that characterizes our group, our Instrumentation & Control (and Power Supply) Group designed and developed a simple, isolated, 1.5A, 4-quadrent, EPICS controlled current source using op-amp technology. The sources power three of the five combined magnets [5].

FIFTH CORRECTOR POSITION

Our Injector's superconducting cavity accelerating unit (9 MeV) produces a vertical kick to the electron beam was corrected by a set of improvised air core coils corrected. To improve the quality of beam from the injector, we decided a characterized, 300 Gauss-cm dipole corrector should replace the improvised correction. Again, no beam line space was available. Fortunately, the beam line at the proposed vertical correction position had a square Panofsky Quadrupole. We again called on the superposed solution described by this paper. In order to produce a uniform dipole field integral, we simply added prototype corner coils to the quadrupole (taken out of the beam line during a down period). By testing, we found the proper ratio of current densities between main coils and corner coils as in the arc Panofsky/Correctors. As before, we wound and installed the final version corner coils to maintain the correct ratio with the current sources powering the top and bottom quadrupole coils. We installed the characterized magnet and powered it with two of the newly developed Current Sources. Figure 5 shows the quadrupole/ dipole installed in the injector immediately after the accelerating unit.

CONCLUSION

This combined function solution is a very handy way to add a corrector dipole in a region where little beam path space is available and a Panofsky Quadrupole is in use. The price is the addition of coils to the corners of the quadrupole, two isolated current sources and the increased complexity of control of the magnets involved. Our solution also shows that to increase field integral uniformity in window frame magnets with high pole gap to pole width ratios, a larger good field region is obtained by adding additional current to the inside corners of the frame above that supplied by a uniform current sheet.

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