Specific Features of Magnet Design for the Duke FEL Storage Ring*

B. Burnham, N. Hower, V.N. Litvinenko, J.M.J. Madey, Y. Wu
Duke University Free Electron Laser Laboratory
Box 90319 Duke University Durham, NC 27708-0319

I. INTRODUCTION

The 1 GeV Duke FEL storage ring is dedicated to drive UV and VUV free electron laser devices. The high brightness and low emittance electron beams needed for these devices demand high performance and tight tolerances on the storage ring magnet lattice. Tight tolerances include close spacing of magnetic elements. In this paper we show how combined function magnets are used to eliminate discrete elements and odd shaped end pieces which cause magnetic coupling, saturation and severe undesireable field nonlinearities. Using this scheme we are able to achieve desireable ring dynamic aperture with only minor modification of existing hardware.

Also included is a discussion of a non-standard septum magnet with stray field compensation which will be employed by this storage ring. The design, testing procedures, and preliminary results are outlined for this magnet.

II. MEASUREMENT PROCEDURES

Magnetic measurements of all magnets were performed prior to installation on the storage ring. In order to facilitate faster data acquisition of large data sets of magnetic fields accurately we make use of a Hall probe array. This array contains eleven individual Hall probes mounted on a non-magnetic plate, each one calibrated using a NMR magnetometer. The elements are separated by approximately 7 mm and the exact distances are measured to within a few microns using a microscope. The voltage signals are sent in parallel to a multiplexer and read by a 20 bit A/D converter in a CAMAC crate to a Macintosh computer running LabView [1]. Magnet power supplies are controlled by 16 and 20 bit DACs and a set of precise shunts and transductors are used for current read back. This particular system was purchased from the Budker Institute of Nuclear Physics in Novosibirsk, Russia, as part of a cooperative effort between Duke University and INP[2].

The high resolution of the array and its electronics yield a magnetic measurement accuracy of better than one part in 10,000 and we can make a two dimensional map with only one pull through each magnet. A set of tracks are used for the precise positioning of the array in each magnet. Since the magnet lattice includes closely spaced elements, it is important that all measurements be taken in a real environment. The magnet test bed at Duke has room to place neighboring magnets around the magnet under test as would be the case when the magnet is eventually placed into the storage ring. In this manner we can better understand the fringe field effects of closely spaced elements.

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Parameters of the Duke FEL storage ring can be found elsewhere [3-4]. The storage ring arcs and south straight section have bilateral lattice symmetry with respect to dipole, quadrupole, and sextupole fields.

III. COMBINED FUNCTION QUADRUPOLES

Natural chromaticity should be corrected by a suitable sextupole component of the magnetic field lattice. The most typical method to generate the sextupole component is by discrete sextupole magnets. In the Duke storage ring, with dispersion free straight sections, the sextupole magnets should be placed in the arcs where only 18 cm of space between each dipole-quadrupole pair is available. It was discovered that the initial attempts to use the dipole magnet with "noses and dimples" as main fixed sextupoles coupled with discrete adjustable sextupoles caused major asymmetric saturation of the dipole and a large amount of magnetic flux between the sextupole yoke and the nearby dipole magnet. The stray fields between the magnets also caused severe non-linear components while dipole magnet saturation caused serious orbit distortions. All of these problems taken together would have made it almost impossible to commission a damping storage ring at Stanford.

We decided to use the arc quadrupole magnets as combined function variable strength main quadrupoles and sextupoles. The arc quadrupoles are wired so that the inner pair of poles (toward the inside of the ring) are independent of the outer pair of poles. When the two sets are excited by the same current there is only a quadrupole moment. With more current separation sextupole and dipole moments can be introduced overlapping the quadrupole. The dipole moment in the magnet offsets the magnetic center (2 mm for designed values of sextupole moments). We have therefore designed the ring so that the central orbit will pass through this new magnetic center.

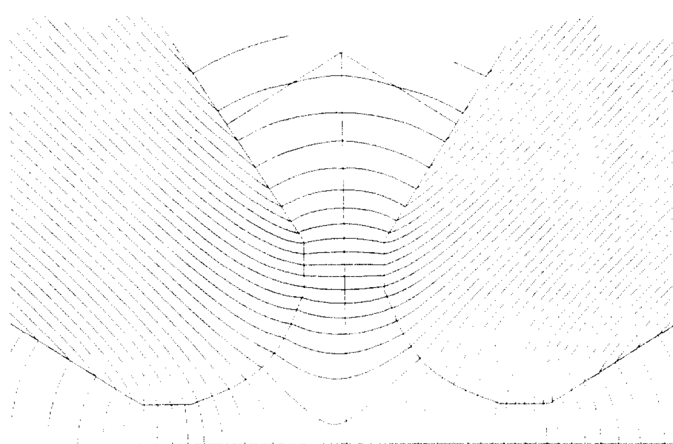

Figure 1. Flux plot from MERMAID.

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Using a two dimensional magnetic field computer code called MERMAID [5] we were able to accurately model the effects of asymmetric current excitation of the quadrupole coils. We found we were able to introduce required sextupole moments into the magnets using this method, and from the results of the MERMAID calculations we began testing the magnets in the same configuration. A sample flux plot from MERMAID for asymmetric excitation is shown in Figure 1.

We have taken large data sets of all of the quadrupole magnets in field mappings and current rampings and created a computer routine to fit the multipole moments using spline interpolation in multi-dimensional space. These data will be used in the control system to achieve the desired strengths in the quadrupole. Typical current settings (varying because of the properties of magnet steel) required to maintain quadrupole and sextupole strengths proportional to the electron energy are shown in Figure 2.

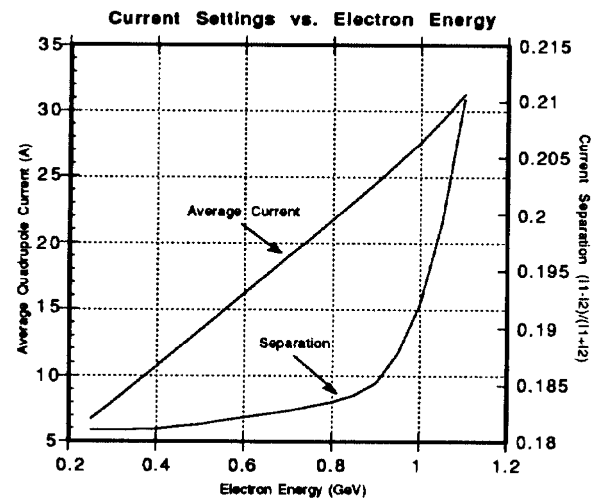

Figure 2. Settings for quadrupole excitation. At 1 GeV gradient is 3.5 kGs/cm, sextupole is 300 Gs/cm^2.

The typical longitudinal distribution of moments is shown in Figure 3.

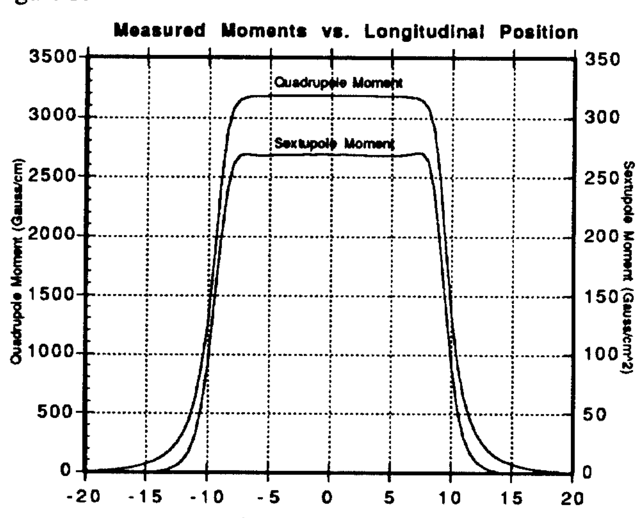

Figure 3. Measured moments in combined function quadrupole.

In order to understand the higher order moments of the quadrupole fields it is necessary to use the measured fields and subtract out the fitted lower order moments. What is left over are the strengths, in this case, for octupole and higher order terms. In the case of the Duke storage ring quadrupoles the lowest moment is dodecapole.

There is a built in correction term for higher orders in these magnets. Figure 4 shows a plot of the integrated moments above sextupole for both the central part of the magnet and the fringe fields. One curve is the integral of the fields inside the magnet steel (without edges), the other for the fringe fields. The two very nearly cancel out overall higher order moments.

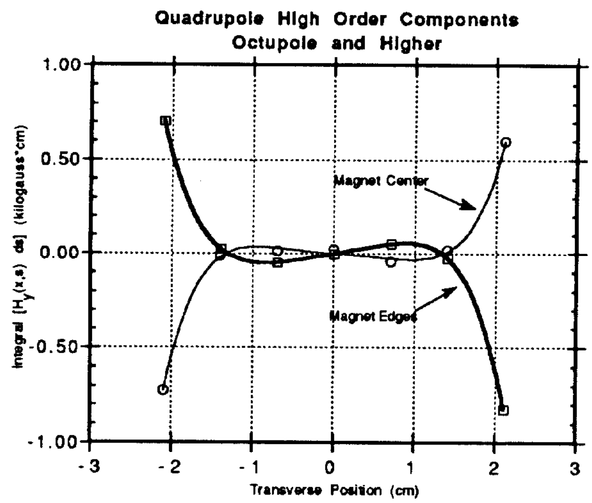

Figure 4. Integrals of higher order moments.

IV. COMBINED FUNCTION DIPOLES

We replaced the odd shaped nose and dimple dipole end pieces with new parallel edge smooth symmetric end pieces required to extend dipole magnetic length. This allows us smoothly to reach saturated symmetric magnetic field behavior up to 20.5 kGs (15.9 kGs is required for 1 GeV operation). We have devised a way to make the dipole magnets combined function while maintaining a higher level

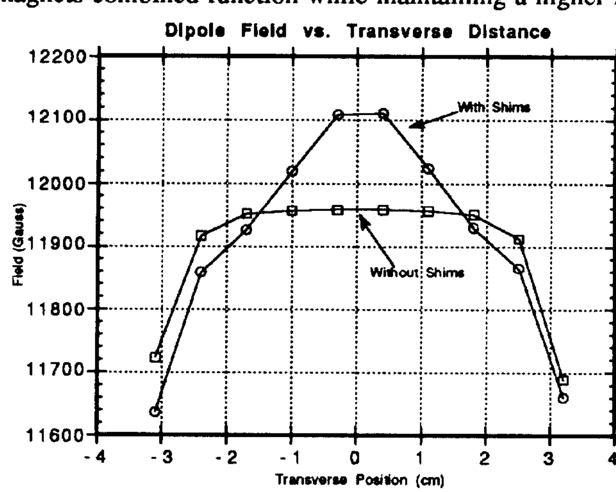

Figure 6. Combined function dipole field.

of symmetry by introducing thin steel shim stock in the center of the magnet This extra "bump" creates a sextupole field of the desired sign as shown in Figure 5. The steel shims themselves are mounted on aluminum strips, so the whole unit is easily replaced if desired. The steel shim stock measures only 6.4 cm long by 2.5 cm wide in a 33 cm long magnet. The measured sextupole moment as a function of longitudinal distance is shown in Figure 6.

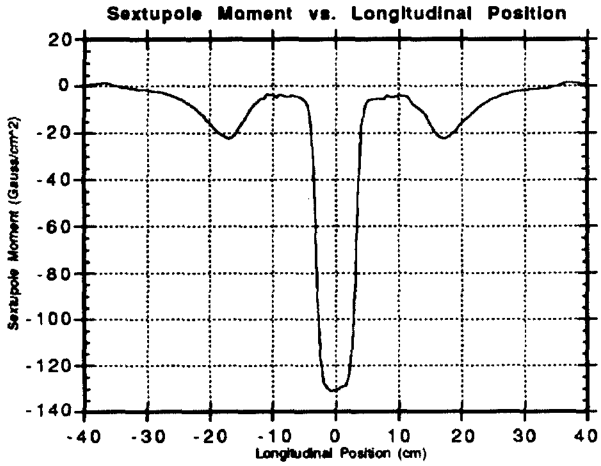

Figure 6. Measured sextupole moment in combined function dipole.

V. SEPTUM MAGNET

A Lambertson type septum magnet is used for injection into the Duke storage ring. We modified the "V" notch angle to 45^o and made the top piece separable for convenience of vacuum chamber installation. The sharp edge measures only 0.5 mm. This magnet employs an 18 turn main coil made from 2 x 66 mm^2 copper sheet and cooling plate mounted on the bottom. The coil is fully enclosed by magnet steel. The stray fields from this magnet are very low because of this isolation, no more than 10 gauss in the "V" notch, where the stored beam passes (see Figure 7). It is only 1 mm away from the main gap where the field is 9 kGs. We have found a way to compensate this field both horizontally and vertically down to a level of less than 1 gauss. The horizontal stray field is caused by asymmetrical saturation of the magnet steel and is compensated by using a five turn coil around one half of the magnet to balance saturation effects. This coil has a total of only 10-15 amp-turns.

Using MERMAID we determined that a flat coil laid into the sides of the notch would be sufficient to cancel most of the vertical field component. The single turn coil measures 4 cm wide by 0.05 mm thick by 1.6 m total length and will carry a current of up to 11 amps. An exaggerated view of the septum magnet is shown in Figure 8.

Stray fields are also prevalent in the groove where the walls of the "V" become vertical. Into this notch is placed another one turn compensating coil which carries roughly one half the value of the current in the flat coil. Assuming this ratio to be constant we can make the flat coil and this particular compensating coil from the same piece of copper sheet. In this fashion we can run the compensation from only one power supply. The magnetic test results confirm the predictions.

The finite permeability of the steel creates a small variation of the magnetic field inside the gap along the pole width which measures 14 cm. This variation was predicted by MERMAID. Even though the field quality satisfies design requirements we suggested one more flat coil (2 x 4 cm wide) just below the notch above the main pole. Only 15-25 A current is required to make the magnetic field uniform (within 0.5 Gauss) in the area of ± 5 cm.

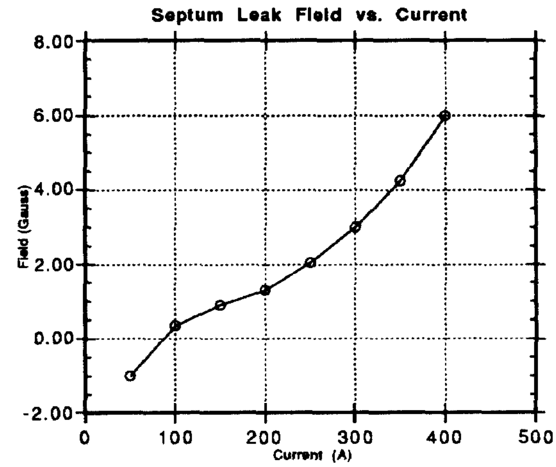

Figure 7. Measured septum leakage field in "V" notch.

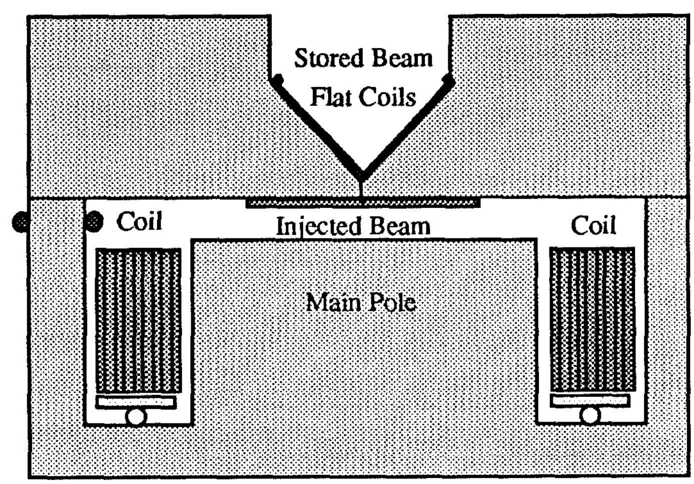

Figure 8. Septum magnet basic design in cross section.

VI. REFERENCES

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