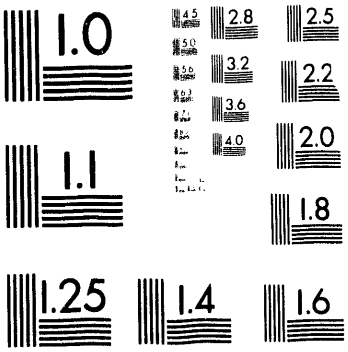
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3-D COMPUTATIONS AND MEASUREMENTS OF ACCELERATOR MAGNETS FOR THE APS

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3-D COMPUTATIONS AND MEASUREMENTS OF ACCELERATOR MAGNETS FOR THE APS*

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Abstract - The Advanced Photon Source (APS), now under construction at Argonne National Laboratory (ANL), requires dipole, quadrupole, sextupole, and corrector magnets for each of its circular accelerator systems. Three-dimensional (3-D) field computations are needed to eliminate unwanted multipole fields from the ends of long quadrupole and dipole magnets and to guarantee that the flux levels in the poles of short magnets will not cause saturation. Measurements of the magnets show good agreement with the computations.

I. INTRODUCTION

The APS, now under construction at ANL, is a 7-GeV positron storage ring to provide x-ray beams for material science, biology, medicine, and other research. The storage ring carries the positron beam for a lifetime of 10 hours or more, producing x-ray beams in the bending magnets and the insertion devices (wigglers and undulators). Two features of the APS impact magnet design, computation, and measurement in ways different from earlier generations of accelerators. First, to achieve the vacuum needed for a ten-hour beam lifetime and to accommodate the photon beam emerging tangentially from the dipole magnets, the vacuum chamber of the APS storage ring is asymmetric, with a large antechamber on the outboard side. The dipole, quadrupole, sextupole, and corrector magnets must accomodate this chamber. Second, the long lifetime requires a very high field quality. Typically the ratio of unwanted multipole components to the principal component must be of order a few hundred parts per million at a radius of 25 mm. Parameters of the storage ring magnets are given in Table I.

The use of 3-D field computations has been a necessity for the design of these magnets. The dipole magnets are 3.06 m long, and different families of quadrupole magnets have lengths of 0.50, 0.60, and 0.80 m. Despite these sizable lengths, the ends of the magnet yokes must be carefully shaped or they will contribute large unwanted multipole fields to the integrated fields. The sextupole and corrector magnets are much shorter (0.2527 m and 0.16 m, respectively), Their effective length is considerably greater than the length of the yoke; consequently, 3-D computations and measurements may show a saturation of the poles not predicted by 2-D computations.

II. RING DIPOLE MAGNETS

For the storage ring dipole magnet, a C magnet design was chosen, with the return yoke on the inboard side as shown in Fig 1. A 2-D design of the magnet was carried out with the finite element code PE2D [1].

As the length of the magnet is 3.06 m and the gap between poles is only 60 mm, most of the magnet is essentially 2-D in behavior; only the last 200 mm of the magnet iron was modeled with the 3-D finite element code TOSCA [1].

The quantity of interest is the integral in the beam (z) direction of the vertical field B_y, integrated in this case from 200 mm inside the magnet to 800 mm outside. For good field quality, this integral should not vary with changes of the integration path in the horizontal (x) direction.

A magnet core with flat ends was found to produce an integrated field with a large, negative sextupole component; away from the shims, material was cut off from the ends in a 45° bevel to correct this. The optimum amount to cut off was found by successive computations to be 0.63" (16.0 mm). End packs with 25.4-mm and 16.0-mm bevels were constructed.

TABLE I
PARAMETERS OF APS STORAGE RING MAGNETS

Magnet	Ring Dipole	Ring Quad	Ring Sext	Horiz. Corr.	Vert. Corr.
Effective Length (m)	3.06	0.80*	0.2527	0.150	0.162
Core Length (m)	3.00	0.79	0.212	0.070	0.070
Strength	0.599 T	18.9 T/m	415.0 T/m^2	0.1562 T	0.1726 T
Integrated Strength	1.833 T-m	12.6 T	100. T/m	0.0234 T-m	0.0280 T-m
Current (A)	452.	386.	160.	127.	124.

* also 0.50 m and 0.60 m

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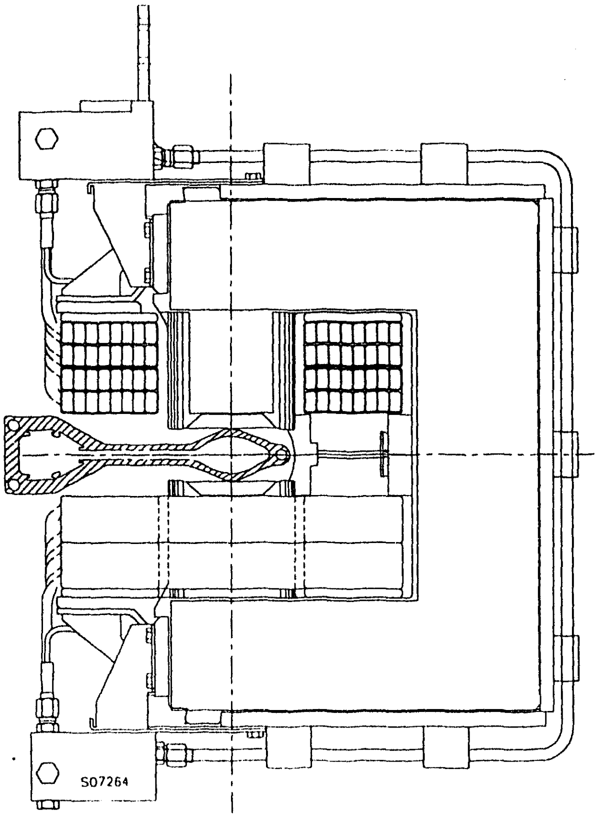

Fig. 1. Cross section of the dipole magnet for the APS storage ring, showing the vacuum chamber in place.

A 1-m-long straight model magnet was fabricated in order to verify the 2-D and 3-D calculations with respect to the lamination geometry and the dimensions of the magnet end bevels. For the measurement of the body 2-D field a 0.5-m-long printed circuit coil was located at the center of the magnet gap. The coil has dimensions of 6.8 mm width and 6.6 mm height. For the measurements of the end-field integrals for the two bevel geometries another 0.5-m coil extended 0.2 m inside the end of the steel lamination and 0.3 m outside of it. The field integrals and their variation in the horizontal direction were measured first by ramping up the magnet current to that for the operation and then by moving the probe coils over a range of ± 45 mm in the horizontal direction. The induced voltages were integrated using voltage-frequency converters.

Comparison of the computed and measured field variation for the 16.0-mm end bevels is shown in Fig. 2. The agreement is seen to be very good. Combining the end variation shown and the variation in the central region of the magnet (not shown) to model a 3-m-long magnet results in a fractional variation of 7.6×10^{-4} in the field integral over the range ± 35 mm in horizontal motion. Measurements of the magnet with the 25.4-mm bevel showed similarly good agreement with the computations.

Computations and measurements for the injector synchrotron dipole magnets also showed good agreement, as has been discussed elsewhere [2].

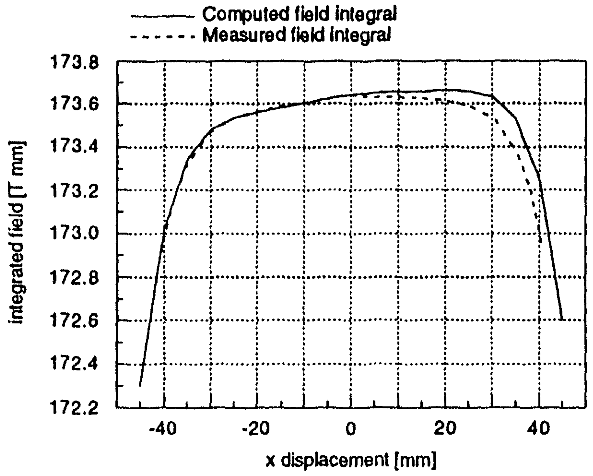

Fig. 2. Variation of integrated field with transverse displacement for the APS storage ring dipole. The integral includes the last 200 mm of iron and the region outside. Upper curve, computation. Lower curve, measurement. The data are normalized to give the same value at x = 0.

III. RING QUADRUPOLE MAGNETS

The ring quadrupoles were the first magnets designed and prototyped for the APS. Extensive 2-D computation went into the design process to determine a shim geometry that was not subject to saturation. After 3-D computations [3] showed that beveled ends could remove the unwanted 12-pole and 20-pole field components, the actual end design was done empirically [4].

IV. RING SEXTUPOLE MAGNETS

After a number of other designs were found not to give adequate field quality, the one in Fig. 3, which exhibits 120° rotational symmetry, was chosen [5]. With this design, in the absence of assembly misalignments there can be no forbidden multipole terms; any that appear in the computation must be artifacts of the mesh or the field evaluation within the mesh. The first allowed multipole beyond the sextupole is the 18-pole. The pole tips were deliberately made narrower than optimum for this magnet to facilitate installing the coils over the poles. A consequence is a negative 18-pole component of about 0.12% at a reference radius of 25 mm. Beam orbit computations show that an 18-pole field of this size has no influence on the dynamic aperture [6].

Electromagnetic codes currently available are in general well suited to the computation of accelerator magnets. The computation of sextupole magnets is an exception to this. In the bore region of a sextupole, the field varies with the square of the radius; the potential, with the cube. Such a variation is best modeled with third-order finite elements, but such elements are not available with most commercially available codes. This limitation can be overcome in part by using a finer mesh with more elements, but at the cost of more computing time and memory. Even with the finer mesh, computing magnet parameters must be done with care since the computed field varies only linearly within each element.

In the 2-D computations, three kinds of triangular meshes were generated over the bore region and compared: (a) an adaptive mesh automatically generated in the polygonal regions of the bore; (b) a regular annular mesh, defined between radii 5 mm and 42 mm and over 30° of arc, then reflected to fill the 180° or 360° considered; and (c) an equilateral triangular mesh generated over a 60° parallelogram then reflected to form a hexagon. In all three cases, an adaptive mesh was used outside the regions specified. It was predicted [7] that an equilateral mesh gives a potential (at the nodes) correct to sixth order. How the potential varies within a triangular element depends upon the interpolation methods supported by the code. We have found some success in using the eight nodes near an element to define a third-order interpolation of a first-order mesh. For the 3-D computations, a hexahedral mesh was used, square in the plane perpendicular to the beam direction. This mesh should result in a potential (at the nodes) correct to fourth order [7].

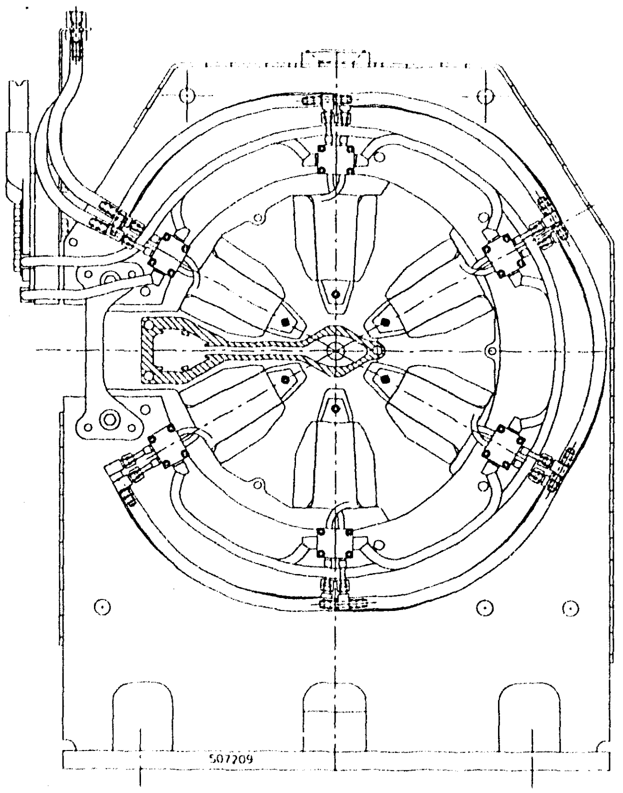

Fig. 3. Cross section of the sextupole magnet for the APS storage ring, showing the vacuum chamber in place.

The sextupole strength and the multipole coefficients (ratio of a specified multipole field to the sextupole field) were measured for a prototype ring sextupole. Both the integrated (3-D) and body (2-D) fields were measured, using a rotating-coil technique [4,5]. Table II gives the measured and computed values of the 18-pole field.

To achieve a higher integrated field strength while avoiding saturation, the length was increased slightly [4]. The values of the parameters in Table I reflect those changes, and are slightly different from those in [5].

Table II
Ratio of 18-Pole to Sextupole Field at 200 A
($\times 10^{-4}$ at the reference radius of 25 mm)

	Computed	Measured
2-D (Body)	-12.2	-11.5
3-D (Integrated)	-13.1	-12.7

V. RING CORRECTOR DIPOLE MAGNETS

The ring corrector magnet, shown in Fig. 4, corrects beam position in both the horizontal and vertical directions. It has six poles and ten sets of windings; six produce a vertical field for horizontal beam correction, and four produce a horizontal field for vertical beam correction. (It is confusing, but unavoidable, that when we speak of the horizontal corrector magnet, we mean the one with the vertical field, and vice versa.) It would provide a sextupole field if the current excitation of all poles were equal in magnitude and alternating in sign. It provides a horizontal field with no sextupole component if the four side poles are all excited equally to the right, and the central poles are not excited. It provides a vertical field with no sextupole component if all six poles are excited in a downward direction, and the central poles have twice the excitation of the side poles. Such fields are adequate in quality for beam correction.

Even more than the sextupole magnets, the corrector magnets have an effective length considerably greater than their core length. (See Table I.) Field levels predicted by 2-D computations, or by 3-D computations with a greater pole length, indicated a central field larger than that predicted by a computation with the true length because for such a short magnet, the flux density in the poles is much higher than it would be for a longer magnet and saturates the poles.

Measurement of the magnet confirmed the presence of saturation and of coupling between the horizontal and vertical excitations, showing four effects. (1) For the horizontal corrector, the ratio of integrated field strength to current decreases with increasing current. (2) For a given excitation of the horizontal correction coils, that ratio decreased with increasing exictation of the vertical correction coils. (3) The sextupole component b_2 of the horizontal corrector, which should be zero, became positive for large values of exciting current. (4) At a given excitation of the horizontal corrector, the sextupole component depended on the excitation of the vertical corrector. Fig. 5 illustrates the first two effects; and Fig. 6 the last two.

To eliminate these problems, the corrector magnet was redesigned with much thicker poles. Computations in 3-D predict that saturation effects will no longer be a problem.

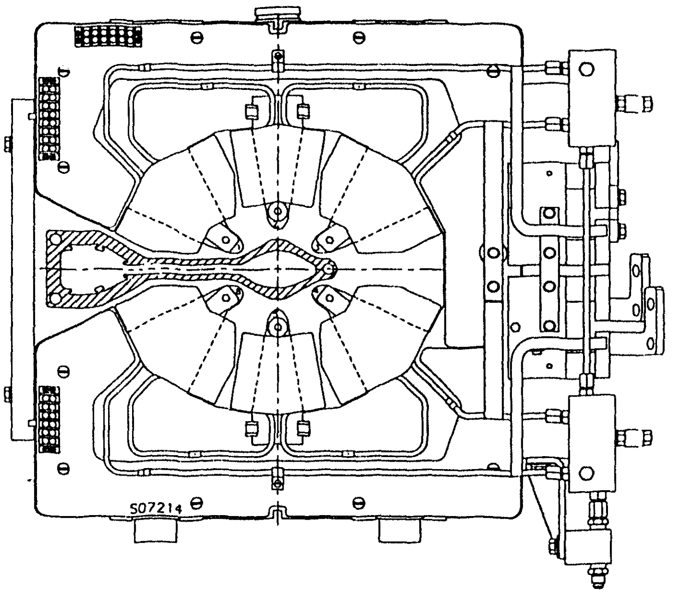

Fig. 4. Cross section of the corrector magnet for the APS storage ring, showing the vacuum chamber in place.

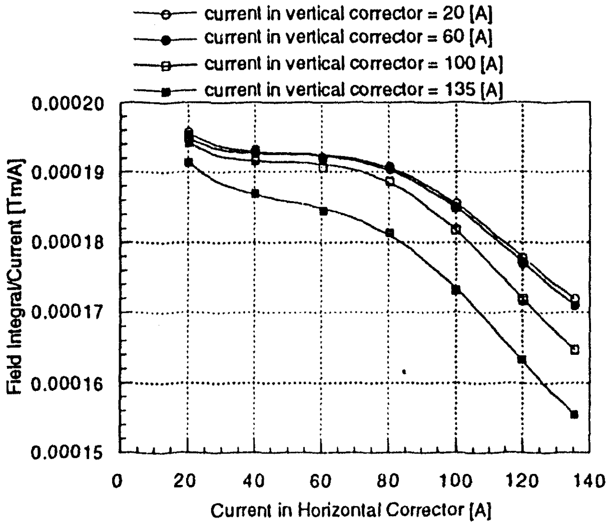

Fig. 5. Ratio of integrated field to current in the horizontal corrector magnet for various values of the current in the vertical corrector. Coupling and other saturation effects are clearly seen.

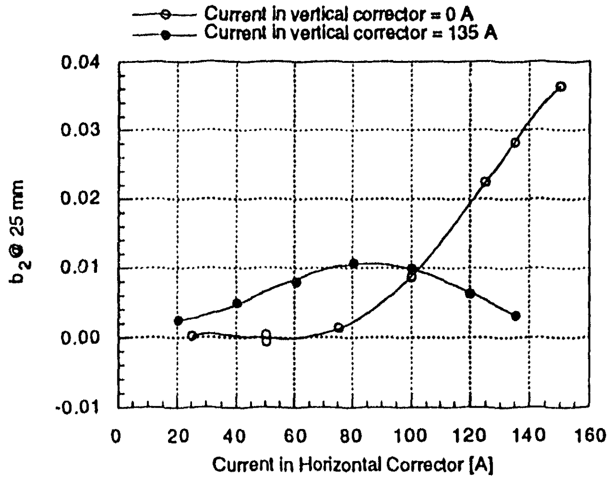

Fig. 6. Sextupole component b_2 (ratio of sextupole to dipole field) as a function of current in the horizontal corrector, for two values of current in the vertical corrector. Coupling and other saturation effects are clearly seen.

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