B. The Magnet System

1. Introduction

The function of the magnet system in the PEP storage ring is to provide the guide field that bends the electrons and positrons in their circular paths and also to focus these particles so that they remain within the machine throughout their many orbits. The system selected for PEP is a separated-function system, meaning that the bending and focusing is accomplished by different magnets. Dipoles provide the bending field while quadrupoles provide the focusing field. A number of correction magnets, such as sextupoles, rotated quadrupoles, wiggler magnets, and low-field bending magnets, are interspersed among the main ring bending and quadrupole magnets, performing beam correction functions as needed.

The design of the different types of magnets in the magnet system is optimized by minimizing the installed capital cost plus ten years' operating cost at 15 GeV. In this way prudent attention is paid to reducing power consumption. Laminated magnets were selected for the main-ring elements both to reduce capital costs and to insure uniformity magnet to magnet by shuffling as explained later in this section.

The main bending system consists of 192 C-type uniform-field magnets, each approximately $5\frac{1}{2}$ m long. Each steel core contains nearly 3,500 $1\frac{1}{2}$-mm-thick laminations having outside dimensions of about $\frac{1}{2}$ m. These laminations are sandwiched between two thick end plates and are held in place by welding straps to both the end plates and the individual laminations. The completed core weighs 9.5 tons. The coils located above and below the beam aperture are of water-cooled aluminum having a conductor cross section of 9×65 mm^2.

There are 240 quadrupoles in the ring. Two styles of quadrupoles having two different apertures will be used: the 216 main-ring quadrupoles have the smaller bore; the 24 insertion-region quadrupoles have the larger bore. The 640-mm long main-ring quadrupoles are of four-piece construction. Each piece contains 430 $1\frac{1}{2}$-mm thick laminations (nearly 1700 per magnet) sandwiched between thick end plates and held together by welding an angle to both the end plates and the laminations. Four core blocks are fitted with water-cooled aluminum coils and bolted together to form one two-ton quadrupole. Two types of insertion region quadrupoles, one of 2 and one of 1.5 m length, are required. These magnets are of two-piece construction, each piece containing two poles. Again, $1\frac{1}{2}$-mm thick laminations are sandwiched between thick end plates and held in place by welding straps to both the laminations and end plates. Half-cores are then fitted with water-cooled aluminum coils and bolted together to form the completed quadrupole. The different lengths are produced by varying the number of laminations stacked for different quadrupoles.

The sextupoles, low-field bending magnets, wiggler magnets, and rotated quadrupoles, unlike the main ring elements, are of solid-core design. All have aluminum coils.

2. Dipole Design and Models

C-magnets were selected for use as the main-ring (flat-field) bending magnets because they afford easy access to the vacuum chamber for infield repair and also because they allow construction and installation of the magnet system independent of the vacuum system. H-magnets would result in smaller magnet cores and consequently a lower capital cost; however, the easy accessibility to the vacuum chamber and the independent construction schedules offered by the C-magnets more than outweigh the slight reduction in capital costs.

The vertical aperture was determined by adding space for the vacuum chamber and clearance to the pole tip to the vertical beam-stay-clear region described in Section II.A.5. For reasons of economy, the apertures of all bending magnets are the same. The horizontal aperture, or good-field region, was determined by adding 20 mm to the maximum beam width to allow for orbit distortions, misalignments, and the sagitta of the curved beam orbit over the total length of the straight magnet. Once the vertical aperture and the horizontal good-field region were determined, the pole width required to produce this field was defined for the dipoles as that region in which $\Delta B/B \leq 0.001$.

The coil-slot area is determined by the optimum current density which for PEP is close to 1 A/mm^2. Since the packaged coils must pass through the magnet gap, the maximum height of the individual coil packages is determined by the gap. Further, analysis has shown that a magnet having single wide coil packages above and below is less expensive to fabricate than one with two or more narrow packages.

The dimensions of the vertical return yoke were determined from structural limitations. Back-leg thicknesses of greater than 100 mm are required so that gap deflections at 18 GeV operation are less than 0.025 mm. The widths of the horizontal yokes were made equal to that of the vertical yoke. The resulting magnet cross section is shown in Fig. 16. Table V presents the important design information.

A computer model of the above design was run using the POISSON program of LBL. Comparative calculations were made for the cross section shown and another cross section with a narrower pole having shims. The narrower, shimmed pole resulted in a slightly increased operating cost since its gap had to be larger than that of the flat pole to accommodate the insertion of the vacuum

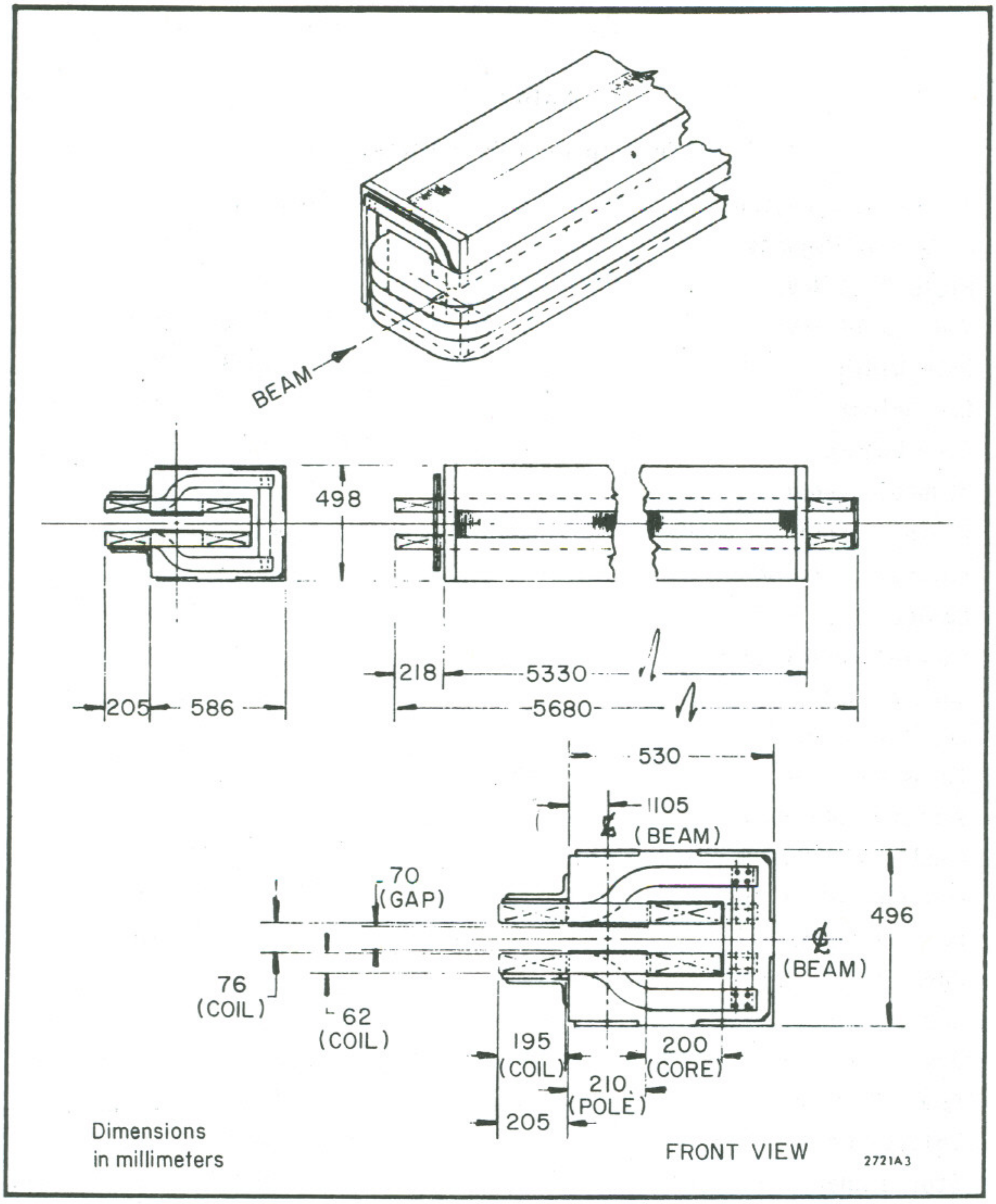

Fig. 16--PEP main ring bend magnet.

TABLE V

PEP Main Ring Bend Parameters

Magnet Designation	70C5400	
Number of Magnets	192	
Field @ 18 GeV	0.3625	T
$\int B d\ell$ @ 18 GeV	1.957	T-m
Pole Width	0.21	m
Gap Height	70	mm
Core Length	5.33	m
Magnetic Length	5.40	m
Width of Useful Field (0.1%)	100	mm
Lamination Height	0.496	m
Lamination Width	0.53	m
Packing Factor (min)	96	%
Core Weight	8580	kg
Amp Turns per Pole @ 18 GeV	10409	A-turns
Turns per Pole	16	
Pancakes per Pole	1	
Conductor Cross Section	65 x 9	mm^2
Cooling Hole Diameter	2 @ 5	mm
Conductor Cross-Sectional Area	546	mm^2
Current @ 18 GeV	650.6	A
Inductance	19.6	mH
Resistance @ 40°C	17.9	mΩ
Power @ 18 GeV	7.58	kW
Voltage Drop @ 18 GeV	11.6	V
Stored Energy @ 18 GeV	4.15	kJ
Coil Weight	242	kg
Number of Water Circuits	2	
Water Flow Rate	9.45×10^{-5}	m^3/sec
Water Pressure Drop	1.38	MPa
Temperature Rise	19	°C

tank between the bumps. This increased operating cost was offset by a reduced capital cost. No final choice has been made; however, the flat-pole version is favored for its support system for the vacuum tank.

A full-size mechanical model of a 60-mm gap, flat-pole main ring bending magnet has been constructed, as shown in Fig. 17. Mechanical and electrical tests are currently in progress and preliminary results indicate good agreement with theory.

After the model was constructed, the gap-height specification was increased from 60 to 70 mm in order to accommodate full coupling between the vertical and horizontal betatron oscillations in the beam. Also the number of turns in the half-coil was increased from 12 to 31 to decrease the size of the current bus in the ring. A further improvement was the winding in of an additional half-turn so that the magnet can act as part of its own bus. Another model, incorporating the above changes as well as improvements in fabrication techniques, is presently being constructed.

3. Quadrupole Design and Models

The best quadrupole field is produced by a magnet having four hyperbolic poles symmetrically arranged about a circular aperture. Four coils, one for each pole, are used to energize the magnet. In the separated-function design, the focusing is done primarily by the quadrupoles. To achieve different tunes, quadrupole (focusing) strengths must be controlled independently, and thus powered independently, of the bending magnets.

The bore, or aperture, of the quadrupoles was determined by the height of the bending magnet vacuum tank for the main ring quadrupoles and by the beam-stay-clear for the insertion-region quadrupoles. The vacuum tank in the arc sections of the ring is common to two bending magnets and two quadrupoles.

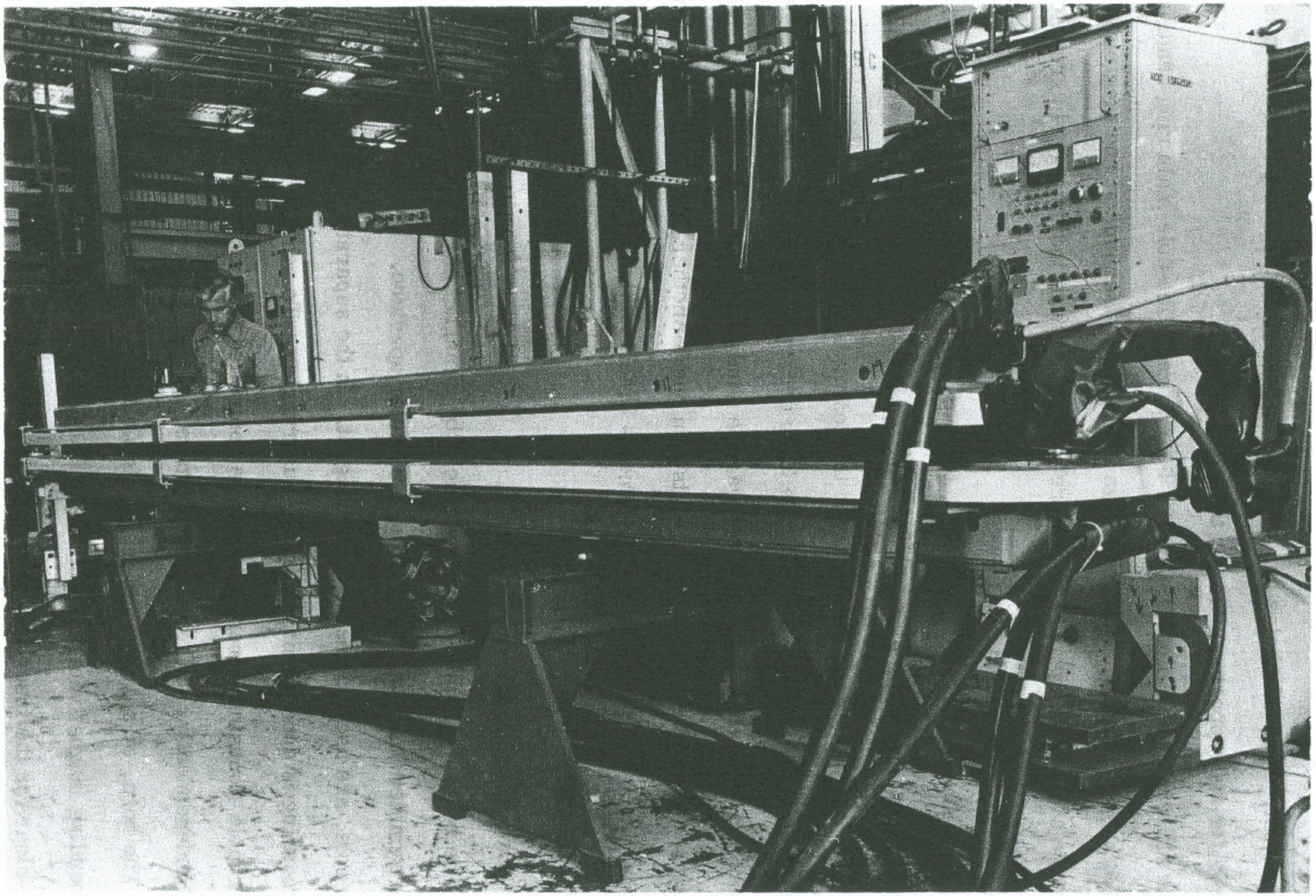

Fig. 17--Photograph of prototype main ring bend magnet.

The bore of the 216 main-ring quadrupoles was determined by minimizing the circular aperture to allow adequate clearance for the vacuum chamber. A 120-mm bore was found to be sufficient. A further reduction in quadrupole bore, and consequently a reduced capital and operating cost for the magnets, could be made if the vacuum chamber at the quadrupoles could be "upset", or made to conform more closely to the quadrupole pole shape. Attempts to effect this configuration have resulted in a loss of vacuum integrity. Further study continues; however, the present design is based on the 120-mm bore.

The bore of the insertion-region quadrupole was determined by the beam-stay-clear requirements in the area of Q2. Using the beam-stay-clear numbers shown in Fig. 12 and providing adequate clearance resulted in a bore of 160 mm. Twenty-four such quadrupoles are required, twelve 2 m long and twelve 1.5 m long.

The field of any magnet can be described as the superposition of the fields of many pure multipole magnets, each having different strengths and numbers of poles. A pure quadrupole would be one in which the field is 100% four-pole. One measure of the field quality of a magnet is the list of ratios of the other multipole strengths present to the strength of the desired multipole. This list is called the multipole content, and is usually expressed in terms of percentages of the fundamental multipole strength. For the main-ring quadrupole, the design multipole content criterion was that all multipoles were to be less than 0.1%. SPEAR experience has shown that insertion-region quadrupoles must have all multipole contents less than 0.01%.

The original main-ring quadrupole design was a scaled-down version of the highly successful SPEAR quadrupole with an increased coil slot to reduce the energy consumption. Four laminated coil blocks were fitted with four 12-turn water-cooled aluminum coils having a current density of 1.74 A/mm^2 at 15 GeV operation. Figure 18 shows the cross section and Table VI gives the magnet's design parameters.

Computer models of this magnet were analyzed using the POISSON program. At low field strengths, the iron in the yoke has essentially infinite permeability and the hyperbolic portion of the pole determines the desired linear dependence of the field. The termination of the hyperbolic poles at the coil slots causes the field to deviate from the optimum linear dependence, but proper shaping of the pole in this area and proper positioning of the coils can compensate for this effect. POISSON was used to determine the required pole shaping.

A full-sized, 127-mm bore model of this magnet was constructed, as shown in Fig. 19. The iron core was found to be within 0.1 mm of the ideal dimensions. After coils were fitted, magnetic measurements were made which indicated that the model more than met the design specification of having all multipoles less than 0.1%. The results of the magnetic measurements are given in Fig. 20. Although the results shown are for a modest excitation, no significant degradation of field quality was observed up to pole-tip fields in excess of 1.25 T, the power supply limit.

The dependence of betatron frequency upon the particle energy, $E = E_0 + \epsilon$, and betatron amplitude, x_β, were calculated for the case where the magnetic multipole field of the model quadrupole was present in all the main-ring quadrupoles. The results are summarized in Fig. 21, where lines of constant tune are plotted in the (ϵ, x_β) space. This quadrupole design is acceptable, and care will be taken to insure that the sextupole and octupole terms of the final magnets do not exceed those of the model.

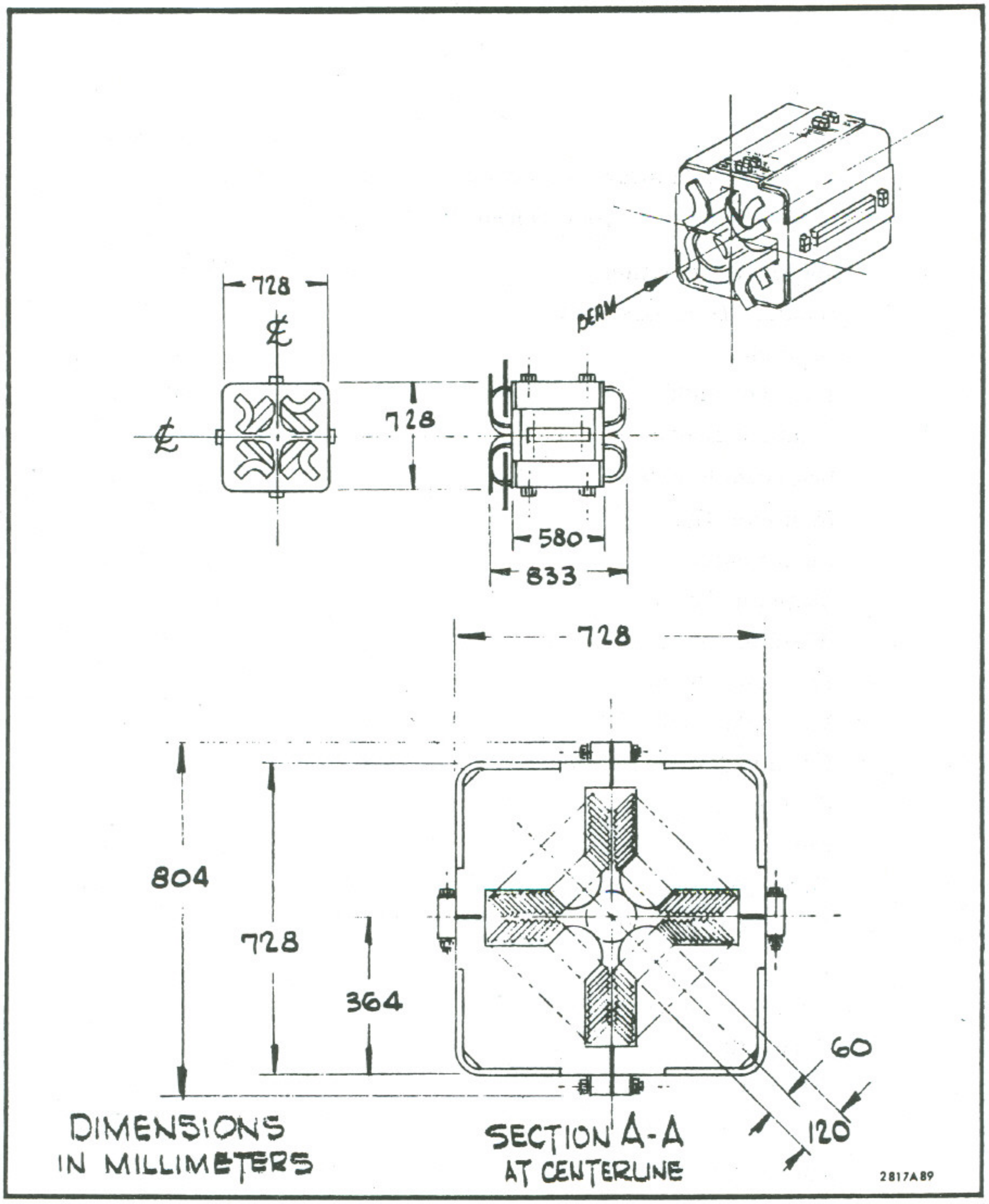

Fig. 18--PEP standard quadrupole assembly (low impedance design).

TABLE VI

PEP Standard Quadrupole Parameters (18 GeV)
(Low Impedance Design)

Magnet Designation	120Q640	
Nominal Peak Gradient	20	T/m
Gradient	12.61	T/m
Pole Tip Field	0.757	T
Gradient Length Product	8.07	T
Inscribed Radius	60	mm
Minimum Gap	34.4	mm
Core Length	0.580	m
Magnetic Length	0.64	m
Width of Useful Field	120	mm
Laminate Height	365	mm
Laminate Width	402	mm
Packing Factor (min)	96%	
Core Weight	1700	kg
Amp Turns per Pole	18062	A-turns
Turns per Pole	12	
Pancakes per Pole	1	
Conductor Cross Section	9×72 mm^2	
Cooling Hole(s) Diameter	2 @ 5 mm	
Conductor Cross-sectional Area	609	mm^2
Current	1505	A
Current Density	2.47	A/mm^2
Inductance	5.14	mH
Resistance @ 40°C	4.47	mΩ
Power	10.1	kW
Voltage Drop	6.73	V
Stored Energy	5.82	kJ
Aluminum Weight	150	kg
Number of Water Circuits	1	
Temperature Rise	35.4	°C
Water Flow Rate	6.85×10^{-5} m^3/sec	
Water Pressure Drop	1.034	MPa

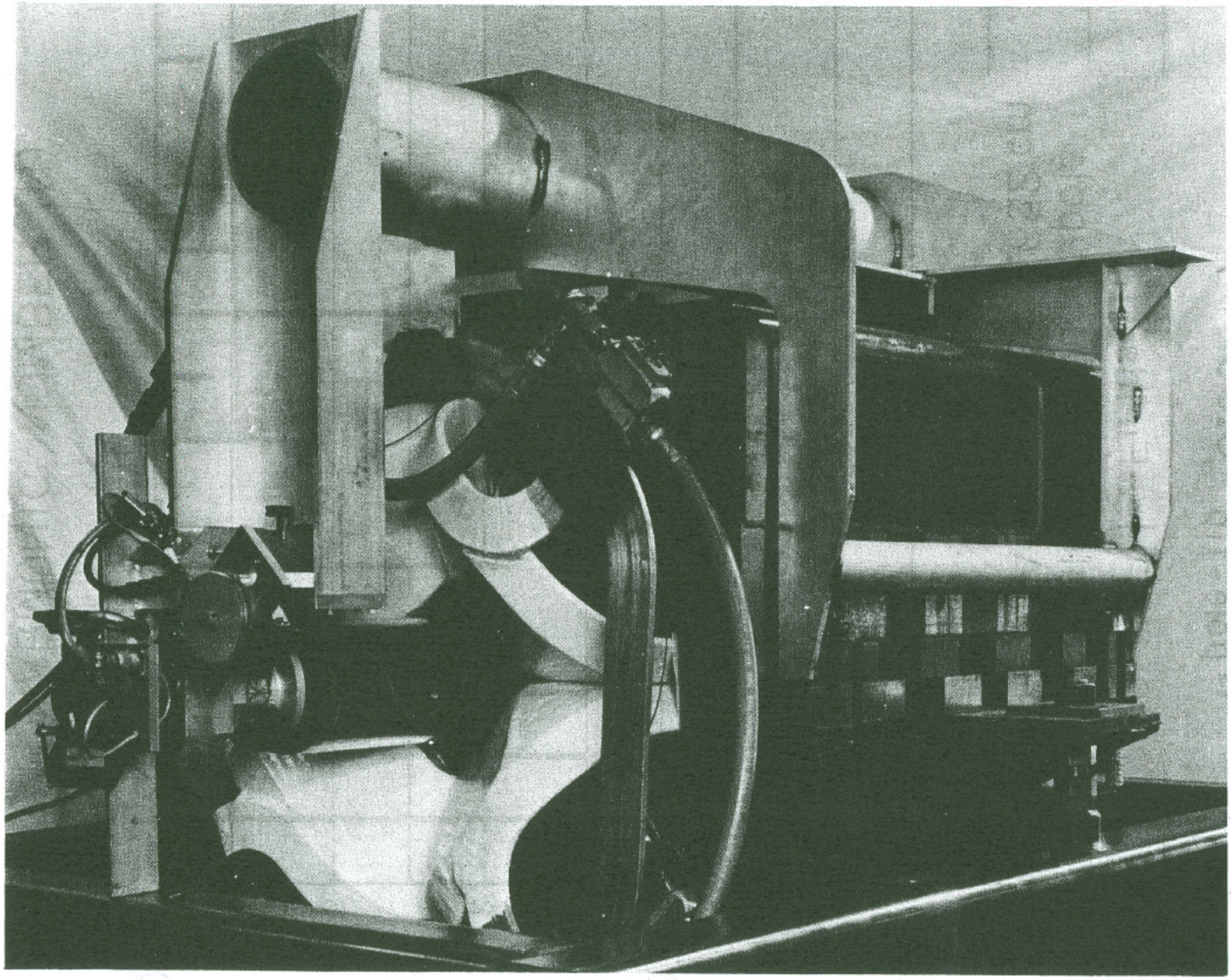

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Fig. 19--Photograph of prototype standard quadrupole.

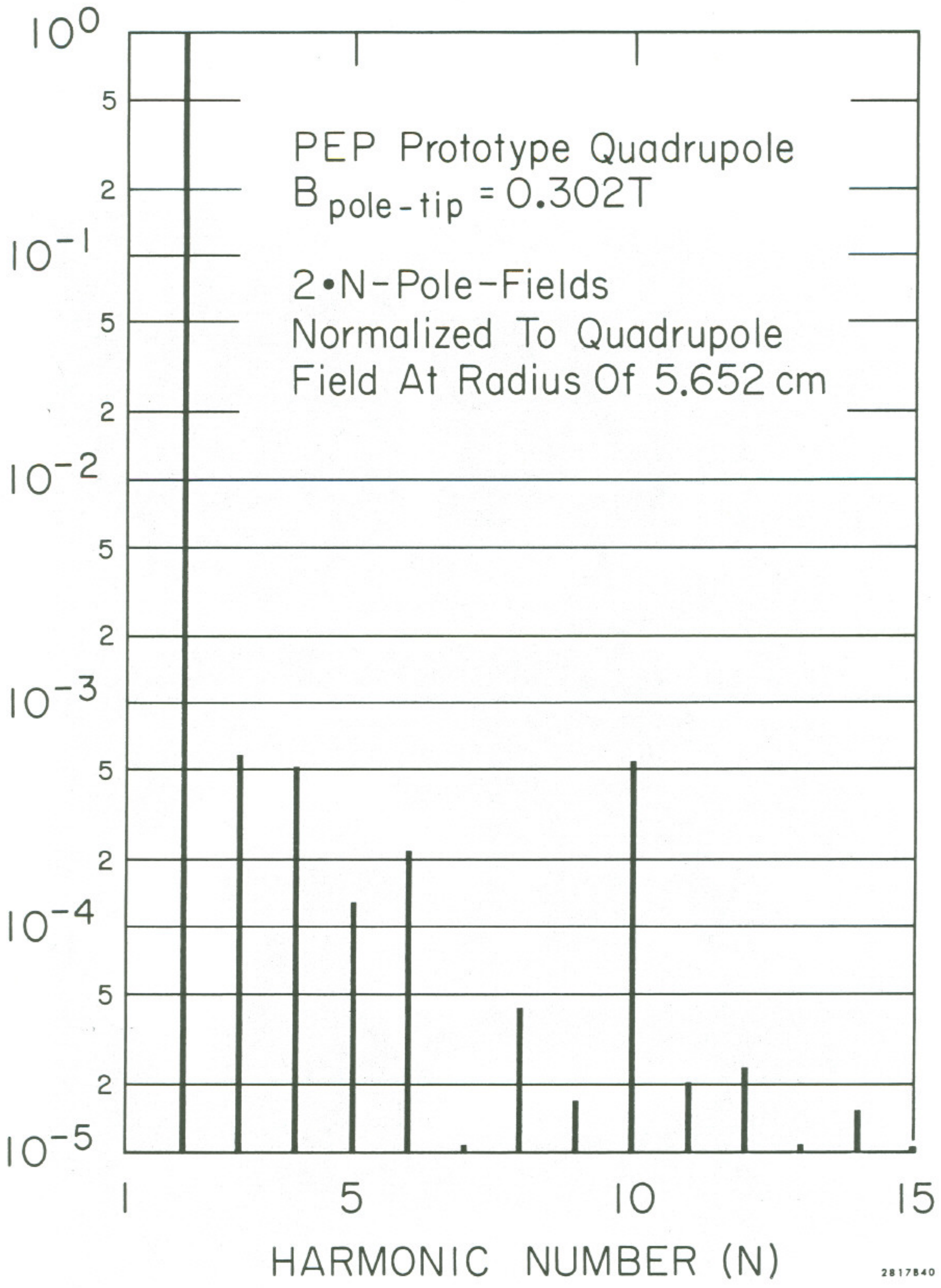


Fig. 20--Multipole content of the prototype standard quadrupole.

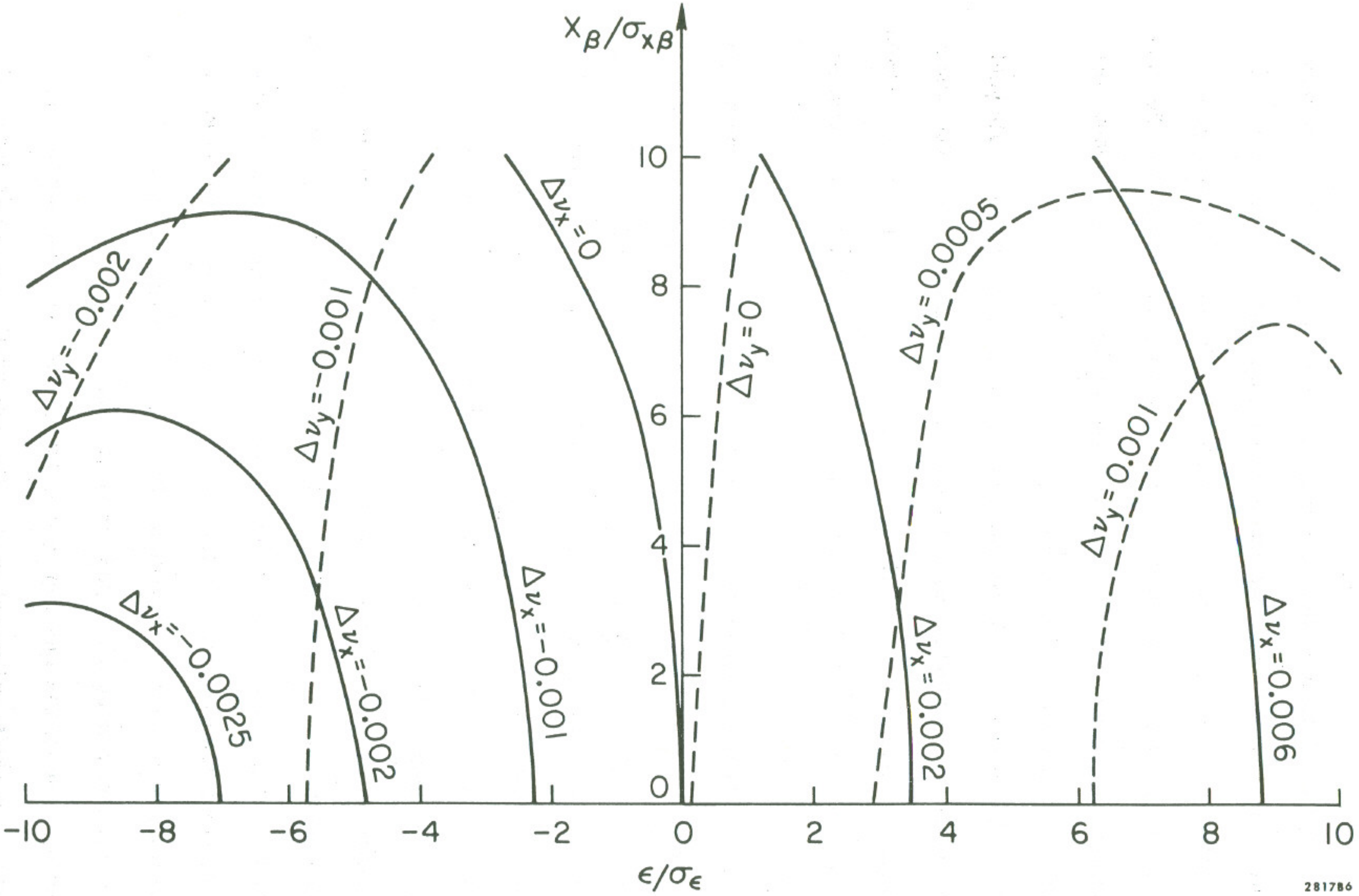


Fig. 21--Effect on the tune due to the multipole content in the standard quadrupole.

Two other quadrupole models utilizing the same strap-coil configurations were built. The second was a two-piece core design with an asymmetric pole configuration. The two-part core was selected for economy in punching and core assembly, and the asymmetric poles were necessary to introduce the wide coil packages into the coil slots. Magnetic and mechanical measurements are currently in progress on these models.

The third model is exactly the same as the first except that the angle holding the laminations and end plates to form a core block is inverted. The assembled magnet resembles a cross, giving the model the name "iron cross". Great difficulties encountered in fabricating straight core blocks have caused this design to be dropped.

To reduce busing costs in the ring, efforts were made to reduce the current of the ring magnets. The number of turns in the bending-magnet coils was doubled, but it was found that increasing the number of turns while retaining the strap-wound coil configuration in the quadrupole was impractical. Thus a fourth design, the high-impedance quadrupole, evolved. This design differs from the original in that it contains nearly five times the number of turns, resulting in a fivefold reduction in current and a corresponding increase in voltage. Figure 22 and Table VII present the main features of this design. Power supplies distributed around the ring would maintain the voltage-to-ground of any one magnet string below 600 V, and the reduced current requirement results in a smaller bus size and hence in lower bus costs. The increase in cost of the coil due to a larger number of turns is offset by the savings in bus cost. This model is presently being fabricated for evaluation.

The insertion-region quadrupole is of two-piece core construction with symmetric hyperbolic optimized poles. The pole profiles were designed and

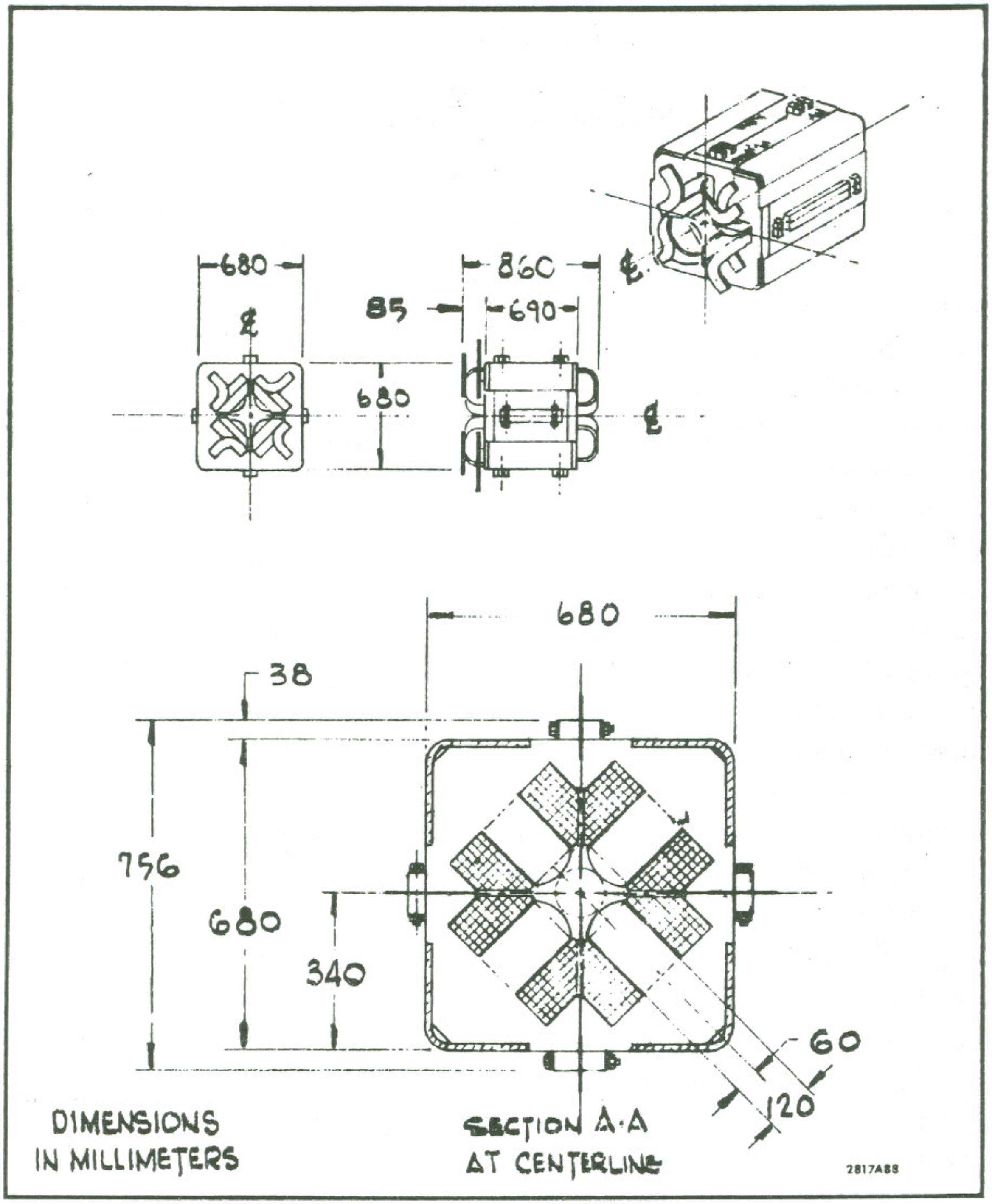


Fig. 22--PEP standard quadrupole assembly (high impedance design).

TABLE VII

PEP Standard Quadrupole Parameters (18 GeV)
(High-impedance Design)

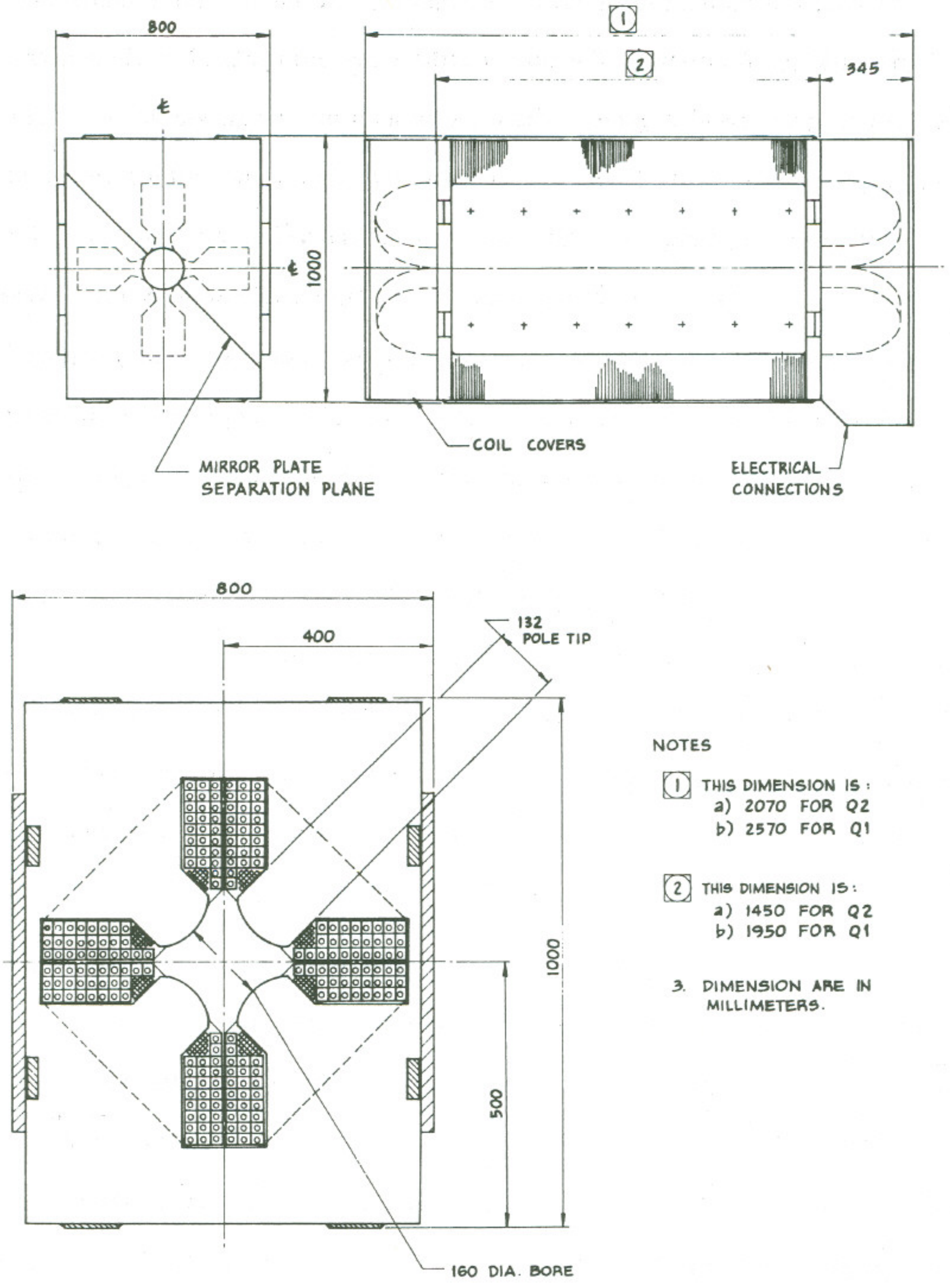
Magnet Designation		120Q750	120Q1000	120Q380
Used for		QF, QD, 2QF, 3QF, 8QF, 8QD, 1QD	Q3, 1QF	9QF
Number of Magnets		180	24	12
Nominal Peak Gradient	T/m	20	20	20
Operating Gradient	T/m	10.76	10.76	10.76
Pole Tip Field @ Operating Gradient	T	0.646	0.646	0.646
Gradient Length Product	T	8.07	10.76	4.09
Inscribed Radius	mm	60	60	60
Minimum Gap	mm	34.4	34.4	34.4
Core Length	m	0.690	0.940	0.32
Magnetic Length	m	0.750	1.00	0.38
Width of Useful Field	mm	120	120	120
Lamination Height	mm	340	340	340
Lamination Width	mm	378	378	378
Packing Factor (min)	%	96	96	96
Core Weight	kg	1700	2316	788
Amp Turns per Pole	A-turns	15412	15412	15412
Turns per Pole		57	57	57
Pancakes per Pole		1	1	1
Conductor Cross Section	mm^2	12.7 sq.	12.7 sq.	12.7 sq.
Cooling Hole Diameter	mm	6.3	6.3	6.3
Conductor Cross-Sectional Area	mm^2	121.3	121.3	121.3
Current	A	270.4	270.4	270.4
Current Density	A/mm^2	2.23	2.23	2.23
Inductance	mH	56.4	75.2	28.6
Resistance @ 40^{o}C	mΩ	112	140	68.4
Power @ 18 GeV	kW	8.17	10.2	5.0
Voltage Drop @ 18 GeV	V	30.2	37.9	18.5
Stored Energy	kJ	2.06	2.74	1.04
Aluminum Weight	kg	150	187.5	91.6
Number of Water Circuits		2	4	2
Temperature Rise	^{o}C	24.6	10.2	11.4
Water Flow Rate	$10^{-5} m^3/sec$	7.95	18.4	10.5
Water Pressure Drop	MPa	1.034	1.034	1.034

optimized using the computer program POISSON. To reduce core costs and improve high-field performance, the pole widths were minimized while maintaining the proper good-field region. The core blocks are constructed of $1\frac{1}{2}$-mm thick laminations sandwiched between 50-mm end plates and welded in a manner similar to the bending magnets. The vertical return yokes are narrower than the horizontal yokes to minimize the horizontal angle subtended by the magnet from the interaction point. Figure 23 shows a cross section of the proposed design and Table VIII gives the design parameters. Three separate aluminum coil packages surround each of the four poles. Two of these packages comprise the main winding and are tied electrically in series with the main ring bending magnet circuit. The third package is a trim winding which enables the individual quadrupoles to be set at their proper operating point.

A model of the insertion-region quadrupole has been built, a photograph of which is shown in Fig. 24. Preliminary mechanical and magnetic measurements have been made which indicate some problems with core assembly. Work is currently under way to rectify these problems.

4. Correction Magnets

Sextupoles. Sextupoles are required to compensate the momentum dependence of betatron oscillation frequency. Space has been allocated for 192 such magnets, one adjacent to each of the main-ring quadrupoles. The criterion for determining the 140-mm aperture was that the magnet must be capable of passing the bending magnet vacuum chamber. Experience at SPEAR has shown that cast-core sextupoles produce sextupole fields of sufficient quality, so this construction will also be used for PEP. The SPEAR sextupoles may be regarded as models. Figure 25 presents the preliminary design and Table IX gives the design parameters. Unlike the other magnetic elements, the coils for these



NOTES

① THIS DIMENSION IS:
  a) 2070 FOR Q2
  b) 2570 FOR Q1

② THIS DIMENSION IS:
  a) 1450 FOR Q2
  b) 1950 FOR Q1

3. DIMENSION ARE IN MILLIMETERS.

PEP interaction region quadrupole

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Fig. 23--PEP interaction region quadrupole.

TABLE VIII

PEP Insertion Region Quadrupole Parameters

Magnet Designation		160Q2000 (Q1)	160Q1500 (Q2)
Number of Quadrupoles		12	12
Rated Gradient	T/m	6.6 (±0.4)	6.6 (±0.4)
Rated Pole-tip Field @ 18 GeV	T	0.53 (±0.03)	0.53 (±0.03)
Inscribed Aperture Radius	mm	80	80
Minimum Gap Between Poles	mm	53	53
Core Length	m	1.95	1.45
Magnetic Length	m	2.0	1.5
Useful Field Width ($\Delta B/B \leq 10^{-4}$)	mm	168	168
Turns per Pole		26 (16)	26 (16)
Rated Current	A	660 (±65)	660 (±65)
Current @ 15 GeV	A	542 (-16)	542 (+9)
Current @ 18 GeV	A	651 (-5)	651 (+22)
Coil Sections per Pole		2 (1)	2 (1)
Conductor Cross Section	mm^2	23 x 20 (6.5 x 6.5)	23 x 20 (6.5 x 6.5)
Cooling Hole Diameter	mm	6.5 (3.5)	6.5 (3.5)
Conductor Area	mm^2	426 (32)	426 (32)
Rated Current Density @ 18 GeV	A/mm^2	1.54 (2.0)	1.54 (2.0)
Resistance @ 40^oC	mΩ	36.5 (260)	29.1 (200)
Rated Voltage (max.)	V	24.1 (16.9)	19.2 (13.0)
Rated Power (max.)	kW	15.9 (1.1)	12.7 (0.9)
Stored Energy @ 18 GeV	kJ	9 (∿0)	7 (∿0)
Inductance @ 18 GeV	mH	42 (16)	32 (12)
Core Weight	kg	9000	6700
Aluminum Coil Weight	kg	594	474
Number of Water Circuits		4 (2)	4 (2)
Water Temperature Rise	^oC	20	20
Water Flow Rate	m^3/sec	1.90×10^{-4} (1.3×10^{-5})	1.52×10^{-4} (1.0×10^{-5})
Water Pressure Drop	MPa	0.82 (0.60)	0.46 (0.30)

Values in parentheses are for auxiliary windings.

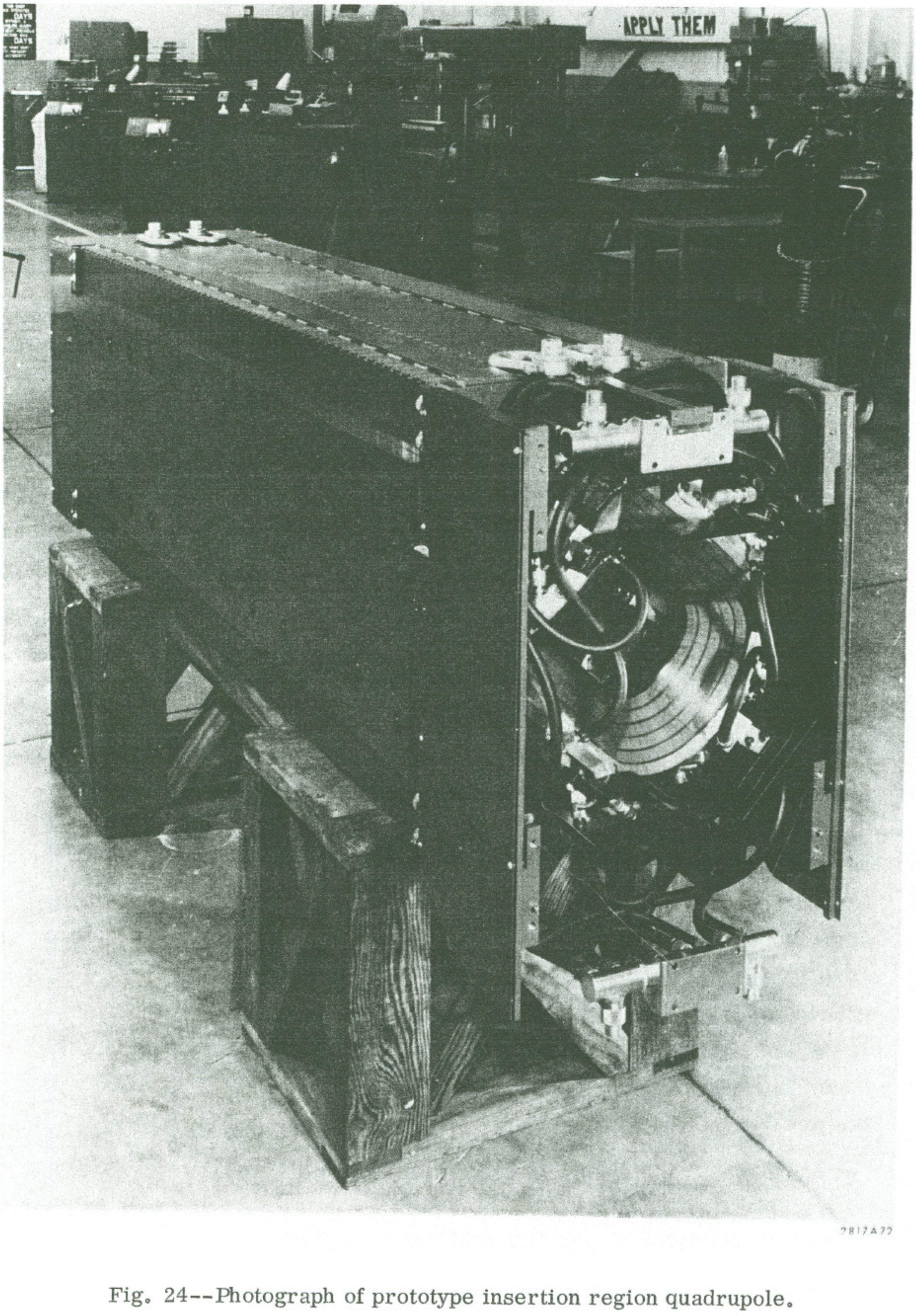

Fig. 24--Photograph of prototype insertion region quadrupole.

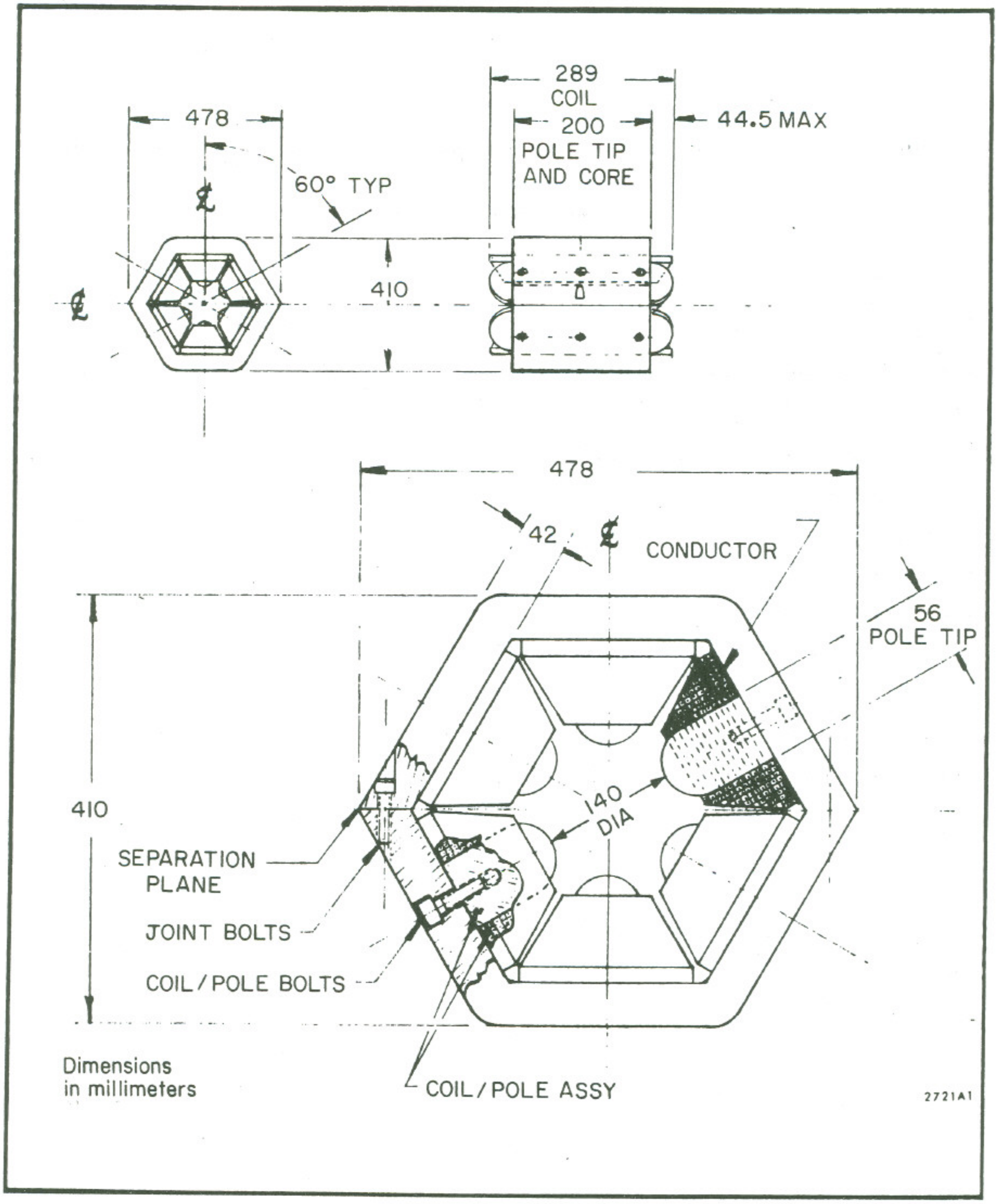

Fig. 25--PEP sextupole assembly.

TABLE IX

PEP Standard Sextupole Parameters

Magnet Designation	140S250	
Number of Sextupoles	162	
Peak Design Gradient	15.0	T/m
Design Gradient at Pole Tip	7.91	T/m
Pole Tip Field @ Design Gradient	0.277	T
Inscribed Radius	70	mm
Core Length	0.20	m
Magnetic Length	0.25	m
Weight of Iron	205	kg
Amp Turns per Pole	5655	A-turns
Turns per Pole	49	
Design Current	115	A
Conductor Size (square copper)	5.8 x 5.8	mm^2
Conductor Area	24.7	mm^2
Current Density	4.7	A/mm^2
Resistance @ 40^0C	91.6	mΩ
Power	1.22	kW
Number of Water Circuits	2	
Temperature Rise	9	^oC
Water Flow Rate	1.6×10^{-5}	m^3/sec
Water Pressure Drop	1.03	MPa

magnets will be made of water-cooled copper. The conductor size is small enough to insure single-length conductors in each coil package, keeping labor costs for fabrication comparable to coils made of aluminum.

Wiggler Magnets. The wiggler magnets, used for control of beam size and beam polarization time, will be of solid-core construction. Their apertures are determined by the beam-stay-clear in the symmetry straight sections in the arcs. The vertical apertures are 50 mm. The horizontal aperture was found by adding the 75-mm beam offset at peak bending power to the good-field region of 70 mm and using the computer to calculate the pole-width required to produce this field. The coil slots were determined by the space available between magnets, the height of the slot being close to half the space available. The width of the slot was found by reducing the power consumption to an acceptable level.

Three identical magnets are required for each wiggler unit. Two of the magnets operate at half the field of the third magnet in the center. All three are connected electrically to produce a net bend of zero. Fields in the central magnet are as high as 2T. Computer optimization of this design is in progress. The preliminary design cross section is given in Fig. 26 and the design data in Table X. Models are planned upon completion of the computer study.

Low-field Bending Magnets. Two low-field bending magnets located in the cells closest to the insertions and having bend angles of 0.8 milliradians are planned to reduce the backgrounds in the interaction areas. The apertures of these magnets are similar to those of the main-ring bending magnets except that the fields required are an order of magnitude less. Table XI gives the design data. Air-cooled copper conductors are foreseen for these magnets.

Other Correcting Elements. Horizontal and vertical steering will be accomplished through the use of trim windings on the sextupoles and bending

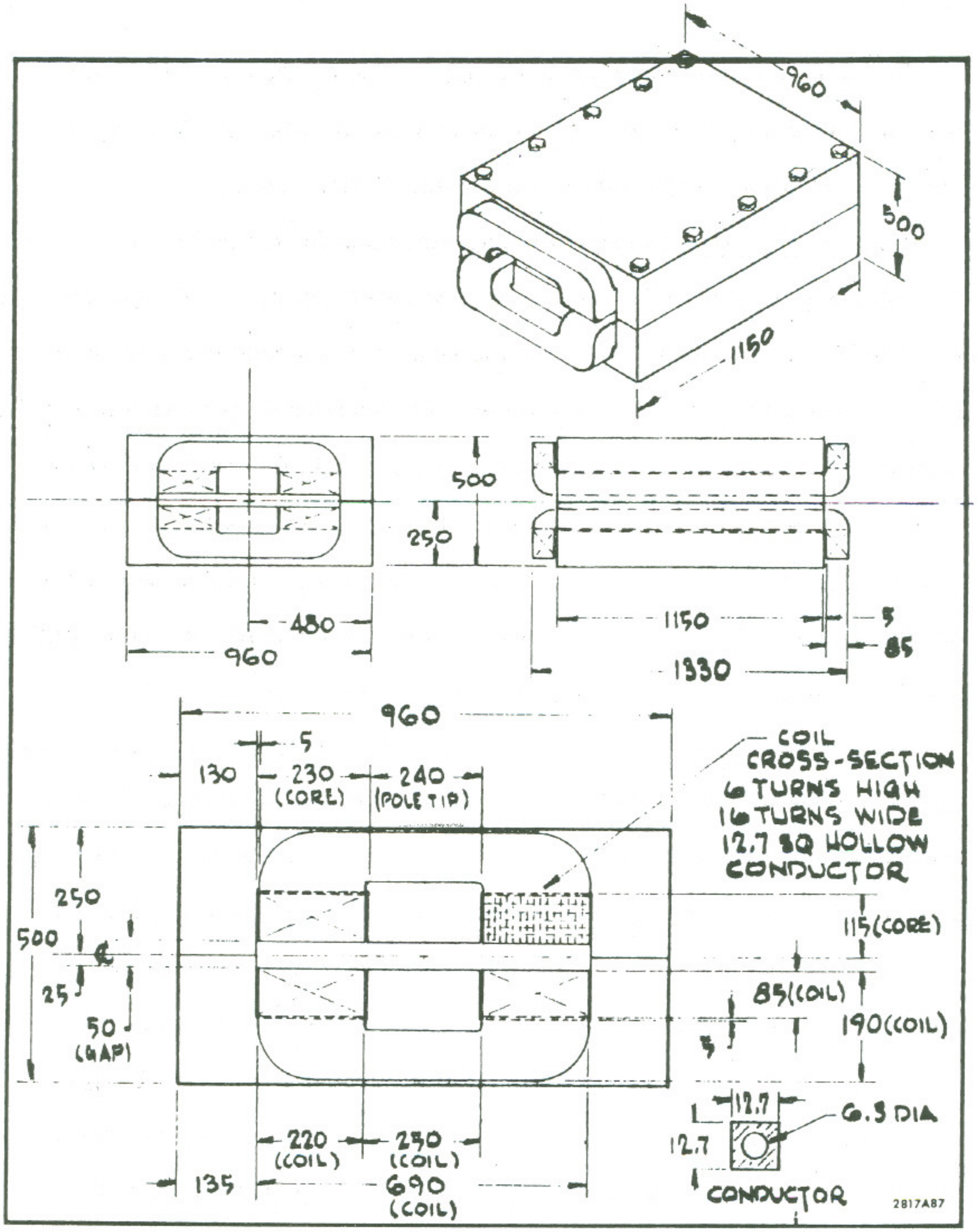

Fig. 26--PEP wiggler magnet assembly.

TABLE X

PEP Wiggler Magnet

Magnet Designation	50H1200	
Number of Magnets	9	
Peak Field	2	T
$\int B d\ell$ @ 2T	2.40	T-m
Gap Height	50	mm
Pole Width	240	mm
Core Length	1.15	m
Magnetic Length	1.20	m
Width of Useful Field ($\Delta B/B < 0.1\%$)	130	mm
Magnet Height	500	mm
Magnet Width	960	mm
Core Weight	3360	kg
Amp Turns per Pole @ 2T	44210	A-turns
Turns per Pole	96	
Pancakes per Pole	3	
Conductor Cross Section (sq. aluminum)	12.7 x 12.7	mm^2
Cooling Hole Diameter	6.3	mm
Conductor Cross-Sectional Area	121.3	mm^2
Current @ 2T	460.5	A
Inductance	968	mH
Resistance @ $40^{o}C$	184	mΩ
Power @ 2T	39.1	kW
Voltage Drop	84.7	V
Stored Energy	102.7	kJ
Coil Weight	123.4	kg
Number of Water Circuits	6	
Water Flow Rate	3.26×10^{-4}	m^3/sec
Water Pressure Drop	1.38	mPa
Temperature Rise	28.8	^{o}C

TABLE XI

Low Field Bend Magnet

Magnet designation	70C2000	
Number of magnets	24	
Field @ 18 GeV	240	G
$\int B d\ell$ @ 18 GeV	480	G-m
Pole width	0.19	m
Gap height	0.07	m
Core length	1.93	m
Magnetic length	2.0	m
Width of the useful field	.080	m
Amp-turns/pole @ 18 GeV	690	A-turns
Turns/pole	23	
Conductor cross section	26.7	mm^2
Cooling	Air	
Current @ 18 GeV	30	A
Resistance	0.172	Ω
Power @ 18 GeV	154	W
Voltage drop	5.13	V

magnets. Tests have been made on the vertical steering capacity of a SPEAR sextupole. The results were published in Ref. 20 and were in general favorable.

Small rotated quadrupoles will be provided for control of the horizontal-vertical betatron oscillation coupling. The bore of these quadrupoles is similar to that of the main ring quadrupole. Depending upon the strength specified and beam-line space available, spare main-ring quadrupoles may be used.

5. Construction

Core Construction

Steel. The cores for the main ring bending magnets, main ring quadrupoles and insertion region quadrupoles are of laminated construction, selected as a result of experience with the solid-core magnets used in SPEAR. There, difficulty was encountered in making one magnet track another at high fields. Because the steel in different cores turned out to have different permeabilities, the magnets had to be relocated around the ring. In PEP the low-field properties as well as high-field excitation must be considered. To maintain high-field uniformity over the broadest range of excitation, a high-permeability at high fields and a low coercivity are required. The best saturation characteristics are obtained in steel sheets having a low carbon content. Subjecting such a sheet to an open-coil anneal in a controlled atmosphere will produce a low coercivity with a variation in properties sufficiently small that with proper mixing an average magnet can be constructed. Steel similar to that supplied FNAL will be used for the PEP magnets in 1.5-mm thick sheets. A thickness of 1.5 mm was selected since the fully decarburized sheet is available in thicknesses of 1.5 mm or less.

Punching and Shuffling. Approximately 700,000 laminations are required to fabricate the main-ring bending magnets and 370,000 for the main-ring quadrupoles. Steel will be supplied to the vendors in sheet or coil, depending upon availability and the vendor's ability to handle coils. Experience with the models has shown that only one punching operation is necessary to produce laminations of sufficient quality.

In order to achieve uniform magnetic properties, it is anticipated that random shuffling of a half store of laminations similar to that used on the CERN ISR will be required. This, together with a random magnetic sampling of magnet steel, will produce the desired uniformity. Magnetic quality assurance measurements will be made on each magnet prior to installation in the ring.

Core Assembly. The laminations for both bending magnets and quadrupoles are stacked between thick end plates on reference surfaces in an appropriate stacking fixture. When enough laminations have been stacked, they are compressed to the desired length at a given pressure. Straps in the form of angles or straight bars are then welded to both the laminations and the end plates, after which the pressure is released. Uniformity in stacking is extremely important to insure constant magnetic properties at high fields, magnet-to-magnet.

The bending magnets are removed from the fixture and supported on an assembly table where the coil-support angles are installed.

Four quadrupole blocks are required to make one magnet. These blocks are assembled and doweled to prevent lateral motion. A V-groove punched in the laminations simplifies this assembly.

Coil Construction

Economic considerations have shown that aluminum-coil magnets are less expensive to fabricate than their copper-coil equivalent. For this reason, both bending magnets and quadrupoles have all-aluminum coils. Further advantages in using aluminum are that it is available in sufficient lengths that no joints are necessary in any of the coils and that, unlike copper, it does not work-harden.

The insulation system proposed for the PEP magnets is the same as that used so successfully in SPEAR. In four years of operation, SPEAR has not lost a single magnet to insulation failure. The system consists of a 0.003-in. thick, 1-in. wide, adhesive-backed mylar tape half-lapped on the conductor, followed by a 0.007-in. thick, 1-in. wide, fiberglass tape butt-lapped over the mylar tape. The entire coil is ground-wrapped using a 0.007-in. thick half-lapped glass tape, after which it is impregnated in a mold under vacuum with a suitable epoxy resin.

The resin system employed in SPEAR may not be sufficiently radiation-resistant for the PEP magnets, but it can be made harder through the addition of alumina. Studies are currently under way to determine the radiation levels in the areas of the coils. PEP-109 indicated levels of 10^7 rads if a 1/8-in. thick lead shield were placed adjacent to the vacuum tank. If such a shield is used, radiation-hardened coils will not be necessary; otherwise, a hardened epoxy system will be required.

Power and Water Distribution

The main ring bending magnets and the main windings of the insertion-region quadrupoles are connected electrically in series. By winding an extra half-turn into the bending magnet coils, the bending magnets can be made to act as their own bus. Jumper cables are provided to connect the top coil of one bending magnet to the top coil of the next. After going entirely around the ring, a jump is made to the bottom coil and the circle is retraced, connecting bottom coil to bottom coil. In this manner, the net ampere turn for the bus circuit is zero.

There are nine independent series bus circuits for the quadrupoles. Air-cooled 600-V cables mounted in trays adjacent to the magnets will be used. The sextupole and wiggler circuits are handled similarly. The circuits for the steering coils are not continuous around the ring but terminate at the nearest insertion region where the power supplies are located.

The proposed magnet low-conductivity water (LCW) cooling system consists of three stainless steel pipes, one supply and a return doubled back on itself to insure that all magnets see the same pressure drop. The cooling water holes on the magnets will be sized so that at 15 GeV there will be a 20°C temperature rise and a 13.6-atm pressure drop. Each arc has its own closed LCW system with the distribution point located at the insertion utility building. The total flow capacity of each arc is 130 gpm, resulting in a heat capacity of 685 kW for a 20°C temperature rise.

Support

The magnet support system is still in the design stage. The supports must provide adjustments of three translations and three rotations, and these six adjustments will be uncoupled as much as possible. The bending magnets will be supported on stands at their points of minimum deflection.

6. Survey and Alignment

Magnet alignment errors in the PEP ring, especially quadrupole magnet offsets, can produce substantial closed orbit distortions. The purpose of the survey and alignment system is to minimize these errors so that very little beam steering will be required to store circulating beam. The long range surveying, over distances greater than about 200 meters, will be performed separately from the short range surveying.

The long range horizontal alignment will be based upon 12 survey monuments to be located by the U. S. Coast and Geodetic Survey at the ends of each long straight section. The survey will take place above ground, and the locations will be transferred down vertical shafts to monuments on the tunnel floor. The long range vertical alignment will be based upon reference levels provided by a hydrostatic level permanently installed in the tunnel.

The short range survey and alignment task consists of locating every ring magnet relative to the two nearest survey monuments. Although several short range survey methods are being considered, one method has received the most attention. This method consists of performing an optical survey using alignment lasers. First, a series of instrument stations will be located at 30 meter intervals between adjacent survey monuments. Then, since a straight line of sight will be available between adjacent instrument stations, it will be a straightforward task to locate ring magnets relative to the instrument stations. The primary advantages of using alignment lasers are high speed and low labor costs. Wherever possible, the radial survey errors will be minimized by measuring offsets to lines of sight rather than measuring small angles.

A conventional optical survey using tapes, theodolites, and alignment telescopes has also been considered, primarily as a backup to the alignment lasers. The conventional method is straightforward but its use will incur higher labor costs. Lastly, automatic surveying systems, including the use of inertial guidance, are being investigated. Such automatic systems would provide extremely high speed surveys and would drastically reduce labor requirements.

7. Power Supplies

Size of Supplies. Groups of magnets are separately powered according to their function in the ring lattice. A listing of these separate circuits is shown in Table XII. In terms of the number of magnets and total power the largest circuit is that of the Bend Magnets and Insertion Region Quadrupoles with a total of 216 elements and 1850 kW of losses. Ten of the remaining thirteen major circuits are various quadrupole circuits; of those only the QF and QD contain more than 12 magnets around the ring. The wigglers and focusing and defocusing sextupole circuits comprise the rest of the major ring circuits.

The circuits discussed above are all independent series circuits with single or multiple power supplies inserted around the ring as necessary to make up the required loop voltage at the maximum current defined for 18 GeV operation. The number of supplies necessary is determined by the choice of 600 V dc as the maximum for each individual supply. Reasons for choosing this maximum voltage are as follows:

1. The maximum voltage to ground is then 600V, which is the standard insulation level for conductors.
2. Supplies can be powered from standard 480V distribution transformers and switchgear.
3. Thyristor and diode voltage ratings of 1500V are available and satisfy the standard 2.5X operating voltage criterion.
4. The current in the circuits will be as low as reasonable (concurrent with good magnet design practice) to reduce the conductor losses around the ring.

The number of 600V supplies to be used in each of the magnet circuits is shown in column 3 of Table XII, and their locations in column 5. For the Bend Magnet circuit the two supplies at each location are plus and minus 600V symmetrically with respect to their common midpoint. The large supplies are located only in regions 4, 8, and 12, with by far the greatest number in region 8, in order to concentrate the control and maintenance functions to a minimum number of locations. Region 8 is the most logical for the heaviest concentration because of its nearness to the Main Control Room. The Ring power supplies will be placed in buildings along with the RF klystrons and their power supplies and the Instrumentation and Control equipment. These buildings will be above ground in the interaction regions. The ac power will come from the 13 kV ring feed system. The cooling water for the power supplies will be on the same system as that for the klystrons and their power supplies.

In addition to the basic design decisions already mentioned, i.e., minimizing the current in the buses around the ring concurrent with a maximum voltage to ground of 600 volts, another goal has been to keep to a minimum the number of different types of power supply circuitry. To this end the Injection System magnet circuits are also designed for a 600V dc maximum level. These large supplies are listed in Table XII, beneath the ring supplies already described, and the magnet systems they power are described in Section II.E. The supplies will be located at the end of the SLAC building in Sector 30. There is adequate 13 kV feeder power already in existence in the area to satisfy the injection needs.

Type of Supplies. Three possible types of Power Supply Controllers have been evaluated for the requirements described above. They are:

1. 6 or 12 pulse, phase-back, thyristor-controlled, three-phase supplies with appropriate filtering on the dc output.
2. Same as 1, plus a transistor bank in series with, or shunted across, the magnet load.
3. Chopper control by a series thyristor from a dc source, where the average output is determined by pulse-width modulation at a fixed repetition rate of at least 1 kHz.

TABLE XII

PEP Magnet Power Supplies

Ring and Injection Choppers

Magnet Circuits	Total Power Required (kW)	No. of 600V dc Choppers	Current Rating (A)	Locations	No. of Magnets per Circuit
B+Q1+Q2	1850	6	700	4, 8, 12	192+12+12
Q3	134	1	300	8	12
1QF	185	1	300	8	12
1QD	114	1	300	8	12
2QF	252	1	300	8	12
3QF	196	1	300	8	12
QF	430	3	300	4, 8, 12	48
QD	420	3	300	4, 8, 12	72
8QF	130	1	300	8	12
8QD	116	1	300	8	12
9QF	99	1	300	8	12
Wigglers	180	1	700	8	9
SD	53	1	300	8	48
SF	26	1	300	8	48
H1	160	1	200	Sector 30	15
H9S	80	1	200	Sector 30	8
H9N	80	1	200	Sector 30	8
Q1S	36	1	100	Sector 30	9
Q1N	36	1	100	Sector 30	9
Q18S	28	1	100	Sector 30	7
Q18N	28	1	100	Sector 30	7

Magnet	Total Power	No. of Circuits	Rating (V/A)	Location
Ring Corrective Elements (not choppers)				
Special Sextupoles	60	5		8
Q1, Q2 Trims	48	24	± 30/100	2, 4, 6, 8, 10, 12
Steering Coils (transitions)	160	48	± 30/100	2, 4, 6, 8, 10, 12
Steering Coils (arcs)	30	96	± 30/10	2, 4, 6, 8, 10, 12
Low Field Bends	7	24	± 30/10	2, 4, 6, 8, 10, 12
Rotated Quad	20	2	± 120/100	8
Remaining Injection Supply Requirements (not choppers)				
Q6N, S thru Q17N, S	64	16	+ 50/100	Sector 30
Bumps	40	8	+ 50/100	Sector 30
Trim T1	3	1	± 50/100	Sector 30
Vertical Bends	36	3	+ 120/100	Sector 30
Trims T2S, N thru T18S, N	12	10	± 120/10	Sector 30
V and H Steering	29	24	± 120/10	Sector 30

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It is predominantly because of the failings of phase-back thyristor control alone (1) that system 2 must be resorted to. The added transistors, with their wide bandwidth, are not so much needed because of the effects of fast ac line voltage perturbations on the magnet current as because of firing circuits imbalance and/or three-phase supply voltages imbalance. Without the transistors the attendant subharmonic ripple present in the output voltage, and therefore in the magnet current, would be out of specification. This ripple is 60 Hz, whether a 6-pulse or 12-pulse rectifier connection is used (normally 360 and 220 hertz ripple, respectively). There is also the problem of subharmonic oscillations caused by single or multiple power supplies interacting through the impedance of the ac feeder system and the firing circuits. An output voltage filter with a low enough corner frequency to reduce these effects to less than 0.01% in the current would have too slow a response to the ramp reference change in the PEP system to be satisfactory.

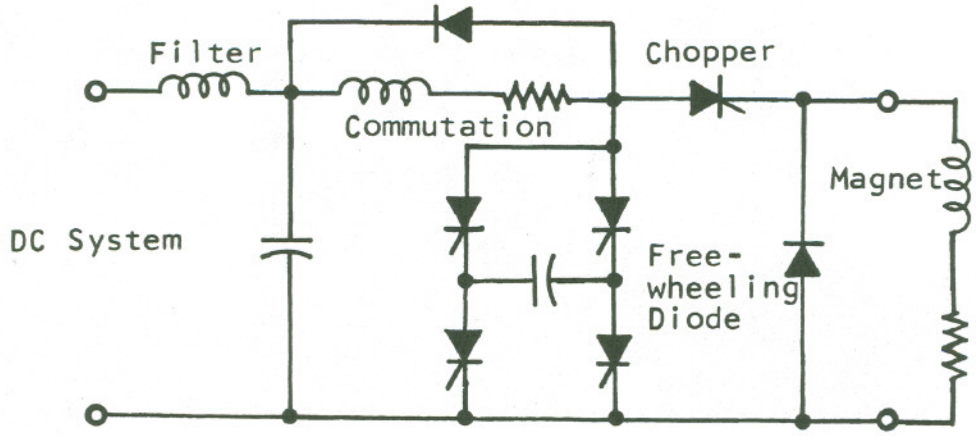
While the combination of transistors and phase-back thyristors solves the limitations of the individual use of either, it substantially complicates the system and increases the problems of maintenance. The cost of the combined system is also at least 30% more than the cost of the thyristor system alone.

The third choice of a chopper system retains the advantages of a phase-back thyristor system without its inherent disadvantages. Because the chopper controls the average value of the output voltage by acting as a switch in series with an unregulated dc supply, the efficiency is similar to the three-phase thyristor system. But the chopper is completely decoupled from the ac supply system by being powered from a filtered dc supply, and therefore the problem of subharmonics in the output is eliminated. Being decoupled also means that the feeder power factor remains constant over the range of operation of the chopper, whereas in the phase-back, ac commutated system the power factor varies directly with the phase-back angle. Utilities usually start charging for reactive VARS when the power factor drops below 0.95, so the chopper will possibly save on future operating costs.

The filter on the dc supply feeding the chopper also means that high frequency noise associated with commutation will not be able to get back to the 13 kV distribution system and pollute other systems. To get the same result with an ac commutated phase-back system, the commutation spikes would have to be minimized by adding reactance, which again would result in an increased power factor and higher output regulation under load. In the output voltage of the chopper frequency components will be nominally filtered to prevent their coupling into other circuits around the ring. No filter beyond that provided by the magnet and the vacuum tank walls is actually necessary to bring the magnetic field ripple to within tolerance.

Because all the chopper circuits are designed for 600V dc operation a common power supply can be used to feed all the choppers in a given location. Thus all the choppers in region 8 will be fed from a 2.5 MW transformer-rectifier set, and those in regions 12 and 4 will each have a 1 MW set. There will be one common filter on each rectifier for all the choppers fed from it, and the rms current drawn from the capacitor will be held down by staggering the basic kilohertz repetition rate fed to the various choppers. This way there are significant savings in transformer costs over using separate units for each circuit. Ground fault detection on each individual circuit will be provided by sensing differential current between the two leads leaving each chopper.

The chopper operates by storing the energy required for commutating the series thyristor switch on a capacitor which is switched into the circuit by a bridge of auxiliary thyristors. The schematic below shows one possible implementation among many of the basic chopper principle. The efficiency of the chopper system is then less (typically by 5-10%, depending on the thyristor turn-off time) than that of an ac voltage commutated system due to the losses incurred in charging the capacitor and turning off the series thyristor. A prototype chopper rated 0-300V dc, 0-1200 amps, is shown in Fig. 27.



The allowable band of tolerance about the set-point of the current reference is ± 0.01%. The maximum rate of change will be not more than 1% per second. An update every 10 milliseconds of a 14-bit DAC is then required for each reference. The currents will all be monitored with transductors capable of ±0.001% operation and with a separate calibration winding built into each of the transductors to provide the means for periodic calibration with respect to previous values and other units in the system. Feed-forward information from the unregulated dc supply voltage will be summed into the control circuit that determines the chopper turnoff time, so that ac line voltage changes will be sensed and corrected during the chopper period in which they occur.

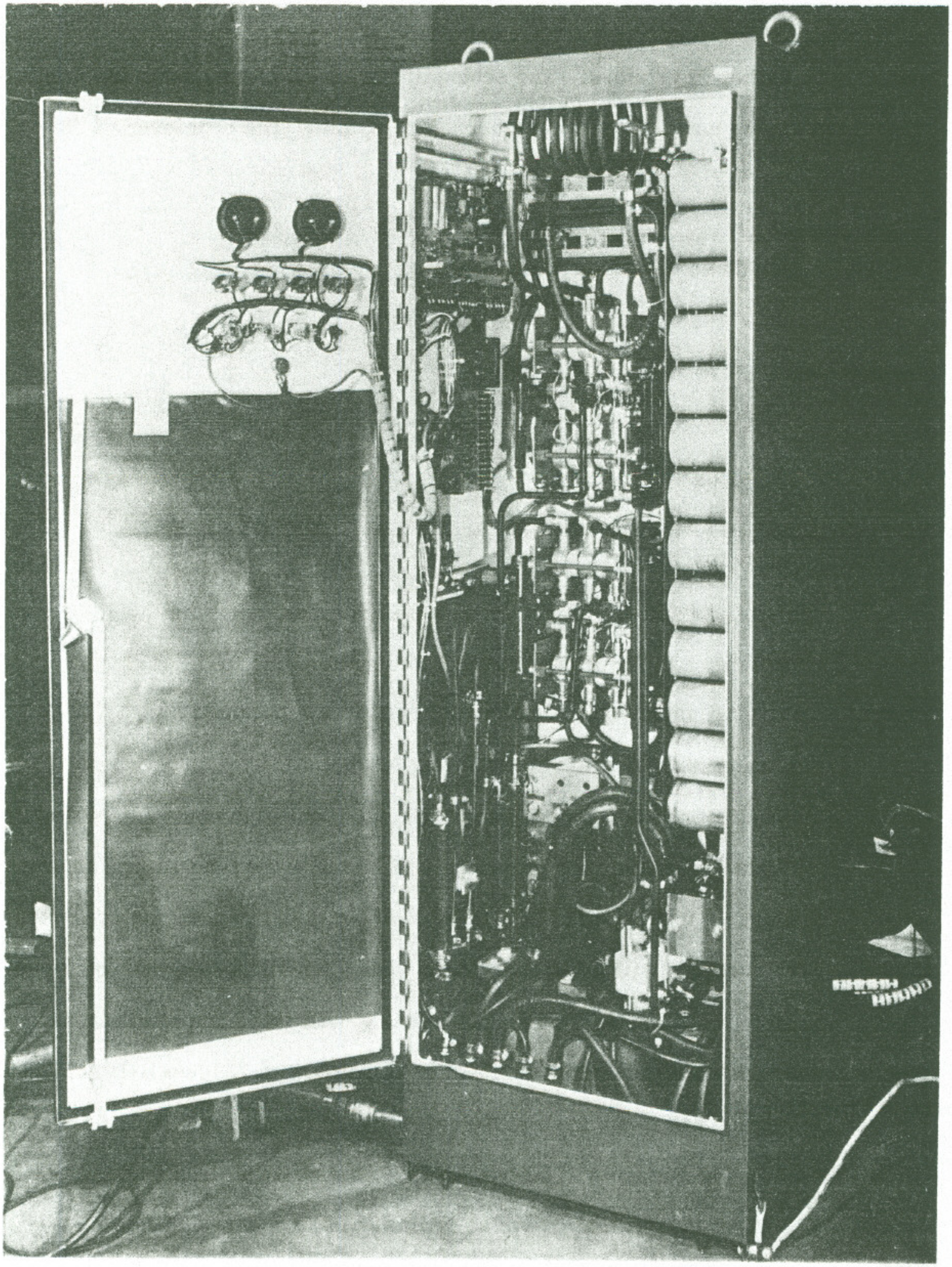


Fig. 27--Prototype chopper for operation from a 300V dc bus at up to 1200A, with a repetition rate of 1 kHz. All the elements needed for ± 0.01% magnet current regulation are included in this package.

Small Supplies. A large number of small supplies are necessary in the Ring and Injection System for special functions such as steering, trimming, low-field bends, sextupoles, and rotated quadrupoles. The trim and steering functions are bipolar and must be adjustable through zero current. Because the loads are single windings, the requirements are well served by continuously controlled transistor actuators. Because of the trimming nature of these supplies the reversal of the polarity applied to the magnet does not have to occur rapidly and therefore a thyristor bridge in conjunction with single polarity supplies can be employed.

The various supplies and their ratings are shown in Table XII. As can be seen in column 4 there are two ranges of power supply voltages required: (1) the 30V and 50V and (2) the 120V. Again, as in the chopper systems, dc unregulated supplies will be used to supply the bulk power at the 30V and 120V level to each ring power supply location with feeders to each individual regulator supplying power as required. The 50V requirement for the injector will employ two of the 30V supplies in series (with transformer taps). Again the emphasis is on minimizing the number of different types of components used.

The transistor-actuator heat-sink and printed-circuit-board package will also be standardized. A Wakefield Heat Sink, Model 180-26 or equivalent, which holds twelve TO-3 transistors, will be used for all applications, with the possibility of "seriesing" or paralleling as necessary. This is an efficient and inexpensive heat sink which is widely available. All components other than the transistors will be mounted on a printed-circuit board which will also serve as a 100-amp emitter bus. The board is purchased with standard 2-ounce copper on one side, but with 7-ounce copper laminate on the other, and with appropriate artwork and with emitter and base pin sockets riveted directly to the board the 100 amps can be brought to a connector at one end of the board. This system provides high reliability and ease of maintenance, along with allowing production line techniques for loading the components. Continually improving ratings in both continuous and switching transistors in the TO-3 package makes it advisable to postpone the transistor selection at this time. Opting for a standard heat-sink package, rather than a particular manufacturer's combination of heat-sink plus transistors, allows the possibility of changing transistors at some later date if an improved type comes on the market or an existing type is no longer available.

The small supplies can be set and will maintain the current setting to ±0.1%. The control and monitoring will be done with DAC's and ADC's located at each actuator.

All the large and small supplies will be fabricated from standard available hardware and mounted in standard racks. Subassemblies for protection, on-off control, monitoring, etc., will be standardized and fabricated for mounting in the racks. Water manifolds will run in trenches below the racks and hose connections will utilize quick disconnects wherever possible for easy maintenance. The 30V dc supplies available at each power supply location will also be used for control functions and conversion to 5V logic level and ± 15V operational amplifier level, making the racks free of 60 Hz ac power. Isolation of individual dc circuits will be by means of a contactor with a fuse for high-level fault conditions. Conductors coming from the bulk dc supplies and going to the magnets will be in trays located above the racks.