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Author
Green, Michael A.

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Introduction

Magnet cost optimization is an important part of the preliminary design of accelerators and storage rings. The storage ring case was chosen for discussion because the power supply does not have a nonlinear effect on the cost optimization, and storage ring size is often predetermined by the physics of the accelerator designed to fill it. The power supply is greatly simplified because no energy-storage device is required, hence coil size can be determined by rather simple formulae. The ring size is assumed to be set in the optimization analysis.

Two types of storage rings were studied by use of MAGHYP[1] (a magnet system cost optimization program). The CERN intersecting storage ring was one of the rings studied[2] because it is a large, high-stored-energy double-ring C-magnet system. The Omnitron storage ring,[3] also studied, represents an opposite extreme from the CERN ring: It is a single heavy-ion storage ring with small H magnets. The third system studied was a hypothetical dc storage ring of the same size, shape, and field as the June 1965 version of the Injector Synchrotron for the 200-BeV Design Study.[4, 5] This ring, representing a case lying between the CERN ISR and the Omnitron ring, was used in studies of aluminum coils for the 200-BeV machine.[6, 7] All three of the rings are designed for protons or heavy ions. The same optimization procedures can be applied to electron or positron storage rings as well.

The MAGHYP computer program calculates the magnet parameters as a function of beam envelope size, magnetic field, effective magnetic radius, coil material, cost factors, and several minor input parameters. The program calculates coil and core dimensions, and power consumption. The program also calculates and optimizes costs of the magnet core, the magnet coils, the power supply, the cooling system, and the cost of operation during the system's useful life. The program is also capable of cost optimization of the high-repetition-rate alternating-gradient synchrotron magnet system. The program does not calculate the effects of magnet size on enclosure and foundation costs.

The Use of Magnet System Cost Optimization During Conceptual Stages

I feel that it is extremely important to make early engineering studies of storage ring or accelerator systems. Early engineering studies can eliminate ring structures (lattices) which may be good from a beam dynamics standpoint,

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but very poor from an engineering standpoint. Lattices should be chosen so that straight sections will occur at places where they are needed. The location and conceptual design of injection, extraction, and tuning elements should begin early.

The best way to solve engineering problems is to avoid them. Many problems that have occurred on some of the existing machines could have been avoided at the time the machine structure was chosen. Early studies of extraction, injection, and secondary elements will permit a reasonable allocation of space for these elements. Vacuum pumps, flanges, and valves should not be ignored. Generous space allowances should be made for such things as end plates, coil ends, and vacuum joints. It is better to allocate too much space than too little; Parkinson's Law will guarantee that the extra space will be filled anyway.

The magnet-cost optimization program has permitted us to calculate optimum magnet size and cost during the conceptual phase. The cost-optimization program also permits the calculation of utility and power requirements at a time when changes can be made to solve some of the utility problems.

I recommend the grouping of functions whenever it is possible. Our experience here at Lawrence Radiation Laboratory has shown that many utility and control problems can be solved by such grouping.

Early magnet-cost optimization permits the enclosure and foundation to be optimized with respect to the magnets. The length of a storage ring enclosure is often determined by the basic characteristics of the injecting machine, but the width and height of the enclosure are functions of magnet size. The foundation cost is a function of magnet weight. Some rough cost factors that have been used at Lawrence Radiation Laboratory to relate tunnel costs to magnet parameters are: \$9.60 per meter of tunnel length per centimeter of magnet pole width, and \$24.00 per meter of tunnel length per centimeter of magnet gap. These cost factors apply for copper magnet coils. Both factors should be increased by 15% when aluminum coils are considered. These tunnel cost factors are incremental cost factors based on the 200-BeV tunnel design. Foundation costs can vary from zero to \$0.75 per kilogram of magnet weight, depending on whether the machine is built on solid rock or on a very soft site.

Magnet-cost optimization is not an end in itself, but must be used in conjunction with cost optimization of the whole machine. The optimum magnet size has a strong effect on space allocation within the straight sections of the machine. Magnet-cost optimization is an extremly important tool for an engineering analysis of the machine during the conceptual phase.

Cost Optimization of the Magnet System and Determination of Magnet Size and Cross Section

The general philosophy used for magnet design is that the core is designed for the maximum excitation and the coil is designed for rms (root mean square) excitation. The rms excitation is dependent on the projected duty cycle of the storage ring magnet system. MAGHYP uses an iterative technique for relating core and coil dimensions, which are interdependent.

The first parameters available from a storage ring structure study are dimensions of the beam envelope and the magnet profile or gradient parameter k. From these dimensions a magnet gap at the central orbit can be calculated:

$$\text{Gap} = 2Z_1[1 + R_1 k] ,$$

$$Z_1 = Dd\,\left[1 - \left(\frac{R_1}{Aa}\right)^2\right]^2 ,$$

$$R_1 = \frac{1}{4k}\left[\left(1+8\,(k\,Aa)^2\right)^{1/2}-1\right] ,$$

where Dd is the minor half axis of the beam ellipse, including vacuum chamber and pole face tolerances, and Aa is the major half axis, including vacuum chamber allowances (see Fig. 1); k is the profile parameter. The above magnet gap equation applies for a wide variety of magnets, including nongradient bending magnets ($k \rightarrow 0$).

Once the gap is known other parameters of the core can be found. If Ax is the useful magnetic field or beam width, magnet pole tip width PW can be calculated from

$$PW = 2\,Ax + (\alpha + 0.125\,B_0)\,Gap.$$

Here B_0 is the peak field at the center of the orbit (in kG) and α is an arbitrary parameter which is dependent on the method used to calculate the magnet pole profile. All the pole profiles calculated by using the computer, such as Halbach's[8] LYBIS program, yield α equaling 0.4. Pole profiles calculated by older methods, such as the Brookhaven AGS, yield α of 0.65. I recommend using a value of α of 0.45. The pole width equation is limited to straight pole magnets with peak central fields of less than 12.5 kG. Reasonable correlations have been made for existing or proposed magnets with central fields up to 12 kilogauss.

When the gap and pole width have been found the back leg and top leg widths can be found. For preliminary study assume that the induction in the back leg equals either 12 kG or the induction in the pole, whichever is greater. For initial optimization studies the back leg width BLW and the top leg width TLW can be assumed to be equal. MAGHYP optimization studies indicate that cost will be minimum if the legs are of nearly equal dimension and there is an induction of 14 kG in each leg. The equations that apply are

$$\left.\begin{array}{ll} BLW = 0.092\,B_0\,(PW+0.7\,Gap) & \text{for C magnets} \\ BLW = 0.046\,B_0\,(PW+0.7\,Gap) & \text{for H magnets} \end{array}\right\} \text{Pole inductions less than 12 kG,}$$

$$\left.\begin{array}{ll} BLW = PW & \text{for C magnets} \\ BLW = 0.046\,B_0\,(PW+0.7\,Gap) & \text{for H magnets} \end{array}\right\} \text{Pole induction more than 12 kG.}$$

$$TLW = BLW$$

The above approximations are reasonable for the magnets which are being optimized here. The only one of the example cases described in the next section follows the back leg and top leg equations given above. The other two cases come close to following the above equations, however.

The only dimensions needed to complete the core are the coil window dimensions and the distance between coils. The coil separation distance often is arbitrarily set for mechanical reasons. The dimension of each of the coil windows is a function of the ampere-turn requirements, the coil packing factor, and the rms current density in the coil conductor. The rms current ratio is defined as

$$\frac{I_{rms}}{I_{max}} = \left[\frac{\int_0^{t_0} \left(\frac{I(t)}{I_{max}}\right)^2 dt}{t_0}\right]^{1/2},$$

where t_0 represents the length of a typical duty cycle, which for the storage ring may be the planned useful life of the machine. The rms current ratio is often little more than a guess. For a storage ring the rms current density can be estimated by using a linearized equation developed in Ref. 7:

$$\eta_{rms} = \left[\frac{A\rho}{B\,Res}\right]^{1/2},$$

$$A = Cc + Fc,$$

$$B = PSc + CSc + Oc\,t_1,$$

where Cc is the incremental cost of the coil in \$/g, Fc represents the incremental cost of the core in \$/g of coil material, and ρ is the coil metal density in g/cm^3; PSc is the power supply cost in \$/W, CSc is the cooling system cost in $/W, Oc is the operating cost of the power supply and cooling system in $/W hr, t_l is the magnet system life in hours, and Res is the coil resistivity in ohm-cm. The rms current-density relation is surprisingly accurate for a wide range of magnet sizes and shapes. Table I gives suggested values for each of the parameters for copper and aluminum coils.

Table I. The current density and cost factors for a linearized magnet system.

Parameter	Units	Copper coils	Aluminum coils
Cc	$/g	0.0066	0.0057
Fc	$/g	0.0016	0.0032
ρ	g/cm^3	8.9	2.7
PSc	$/W	0.10	0.10
CSc	$/W	0.16	0.20
Oc	$/Whr	8×10^{-6}	8×10^{-6}
t_l	h	6.75×10^4	6.75×10^4
Res	ohm-cm	1.72×10^{-6}	2.88×10^{-6}
η_{rms}	A/cm^2	224	98

By use of the rms current densities given in Table I, the coil packing factor and the coil aspect ratio and the dimensions of the coil and the core can be determined. The magnet ampere-turn requirement can be found by iteration of the equation

$$NI = NI_{gap} + NI_{iron} .$$

When the coil and core dimension are found the weights of the coil and core can be found. MAGHYP does all of the above operations, including calculations for the magnet ends. The cost of the coil and core are calculated by using an incremental cost equation of the form

$$\text{Core (or coil) cost} = E + (d\$/dw)W .$$

For the coil the d$/dw term represents the Cc term in the current density equation. For copper d$/dw is $3.00/lb, for aluminum $2.60/lb, and for core steel $0.40/lb. The E term has no effect on cost optimization, but is included because it is necessary that the total cost be accurate.

The results of cost optimizing the three storage rings in the next section of the paper prove the usefulness of the simplified linearized equation for rms current density. The equation has been found to be accurate within 10% for a large number of magnet systems calculated with the foregoing cost factors. The optimum rms current density will vary considerably from the values given in Table I when other cost and useful-life data are used. The linearized equation shows why there is a cost advantage in using aluminum coils for storage-ring magnets.

A Comparison of the Cost of the ThreeStorage Rings Optimized by Using MAGHYP

The MAGHYP program calculated the dimensions of the core and the coil and the power consumed by the magnet coils for varying rms current densities for the three sample storage rings. Table II presents the magnet parameters that do not vary with coil size for the three magnet systems.

Table III presents the cost parameters used in the study of the three storage ring systems. The cost parameters used for this table are based on the costs, in U. S. dollars, used for the 200-BeV study. It should be noted that the cost parameters for the CERN ISR would be quite different if European costs were used.

The results of the cost optimization are presented in Table IV and Fig. 5. The optimum magnet cross sections for each of the three storage ring systems are shown in Figs. 2, 3 and 4.

Table II. Magnet parameters which do not vary with coil current density for the three example storage rings.

Magnet system parameter	Omnitron storage ring (Ref. 3) 1966	Hypothetical storage ring like the 1965 200-BeV injector synchrotron	CERN intersecting storage rings (Ref. 2), 1964
Storage ring type	single ring	single ring	two intersecting rings
Ring radius, average m	19.13	98.6	150.0
Magnetic radius, m	7.24	42.6	79.2
Effective magnetic radius (which determines iron dimensions), m	7.24	42.6	72.7
Number of bending magnets in system	64	80	264
Average F and D magnet profile k, m^{-1}	3.836	4.419	3.095
Magnet gap at the beam center, cm (in.)	5.31 (2.09)	8.14 (3.40)	10.0 (3.94)
Beam envelope size, cm	4×8	6×14	5×16
Peak field, kG	10.0	7.12	12.0
Magnet type	H	C	C
Pole width, cm (in.)	16.0 (6.5)	25.4 (10.0)	35.5 (14.0)
Back leg width, cm (in.)	10.2 (4.0)	20.3 (8.0)	35.5 (14.0)
Top leg width, cm (in.)	8.9 (3.5)	19.1 (7.5)	35.5 (14.0)
Coil separation, cm (in.)	None	15.2 (6.0)	21.0 (8.28)
Ratio of rms current to peak current assumed	0.9	1.0	0.8
Coil packing factor	0.65	0.65	0.65
Peak gap ampere-turns	42 258	48 852	95 506
Magnet gap stored energy for the system (MJ)	0.212	1.562	12.648

Table III. Cost coefficients used to calculate cost of the core, coil,water-cooling system, power supply, and operation.

		Omnitron storage ring	Hypothetical storage ring like 1965 design for 200-BeV injector synchrotron	CERN intersecting storage rings, 1964 version
Copper coils	E, M$	0.068	0.203	2.860
	d$/dw, $/lb	3.00	3.00	3.00
Aluminum coils	E, M$	0.068	0.203	2.860
	d$/dw, $/lb	2.60	2.60	2.60
Core	E, M$	0.052	0.471	4.060
	d$/dw, $/lb	0.40	0.40	0.40
Aluminum water system cost, $/kW		200.	200.	200.
Copper water system cost, $/kW		160.	160.	160.
Power supply cost, $/kW		102.	102.	102.
Operating cost, $/kWh		0.008	0.008	0.008
Economic life, h		67 500	67 500	67 500

The optimum current densities given in Table IV and Fig. 5 indicate that the simplified current density equation, given in the previous section, is applicable for a wide range of dc magnets. The computer studies also indicate a considerable cost saving than can be achieved using aluminum coils. The MAGHYP results show that cost savings of 10 to 15% can be achieved in the total cost of the storage ring system. Lawrence Radiation Laboratory studies show that this cost saving will extend over the full range of economic life.

The 13% saving on the Omnitron aluminum coils over copper coils does not take into consideration the reduction in coil fabrication cost that will occur as a result of the strap configuration. The Omnitron coils have a higher packing factor that was assumed in the MAGHYP calculations. Cost savings of 20% on the Omnitron storage ring may be possible.

The additional space that would be occupied by the magnet with aluminum coils must be considered. The space allotment problem should be considered during the lattice selection process. The cost saving that can be achieved with aluminum coils can occur only when the coils are fully optimized. The split H core becomes attractive when one considers the cost saving that can be obtained by using strap coils similar to the Omnitron coils. The split H eliminates the size limitation of coils due to the fact that they must be installed and removed through the magnet gap. One important limitation with aluminum coils is the need for a single-metal closed-circuit water-cooling system.

Table IV. Physical parameters and costs of the optimized magnet systems.

	Omnitron storage ring		1965 200-BeV injector synchrotron as a storage ring		CERN intersecting storage ring, 1964 version	
Coil type	Copper	Aluminum	Copper	Aluminum	Copper	Aluminum
rms current density, A/cm^2	229.0	100.3	223.8	98.6	230.6	100.9
Lamination width, cm(in.)	57.1 (22.5)	67.9 (26.7)	64.5 (25.4)	74.1 (29.2)	94.2 (37.3)	106.6 (42.1)
Lamination height, cm(in.)	43.0 (16.9)	56.0 (22.0)	71.5 (28.1)	80.6 (31.8)	116.7 (45.3)	126.8 (50.0)
Coil width, cm(in.)	10.2 (4.02)	15.5 (6.09)	18.7 (7.40)	28.3 (11.16)	23.2 (9.27)	35.4 (14.0)
System coil weight, lb	4.34×10^{4}	3.22×10^{4}	2.63×10^{5}	1.87×10^{5}	1.52×10^{6}	1.10×10^{6}
System core weight, lb	1.46×10^{5}	1.98×10^{5}	1.69×10^{6}	2.05×10^{6}	1.50×10^{7}	1.77×10^{7}
System power consumption, kW	220	165	1275	925	7800	5700
Estimated coil cost, M$	0.198	0.152	0.993	0.689	7.422	5.726
Estimated core cost, M$	0.111	0.131	1.149	1.290	10.060	11.145
Magnet cost, M$	0.309	0.283	2.142	1.979	17.482	16.871
Power supply cost, M$	0.022	0.017	0.130	0.094	0.796	0.581
Cooling system cost, M$	0.035	0.033	0.204	0.185	1.248	1.140
Magnet system capital cost, M$	0.366	0.333	2.476	2.258	19.526	18.592
Magnet system operating cost for 67 500 h, M$	0.118	0.088	0.683	0.496	4.180	3.055
Magnet system total cost, M$	0.484	0.421	3.159	2.754	23.706	21.647

Conclusions

Cost optimization of accelerator and storage ring magnet system is an important part of the conceptual design phase. Cost optimization of the magnets will permit one to calculate the size, power requirement of a lattice. An early knowledge of the magnet parameters will permit an engineering analysis of straight-section use, enclosure and foundations, and utilities. An early engineering analysis is essential for the best possible machine to emerge. Cost optimization of the magnet system is an important part of this analysis.

The current density in the coils is predictable within 5% for a large number of dc magnet types. Our studies show that considerable cost saving can be achieved by using aluminum coils. This cost saving can be realized by working within the aluminum coil design limitations.

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List of Figures

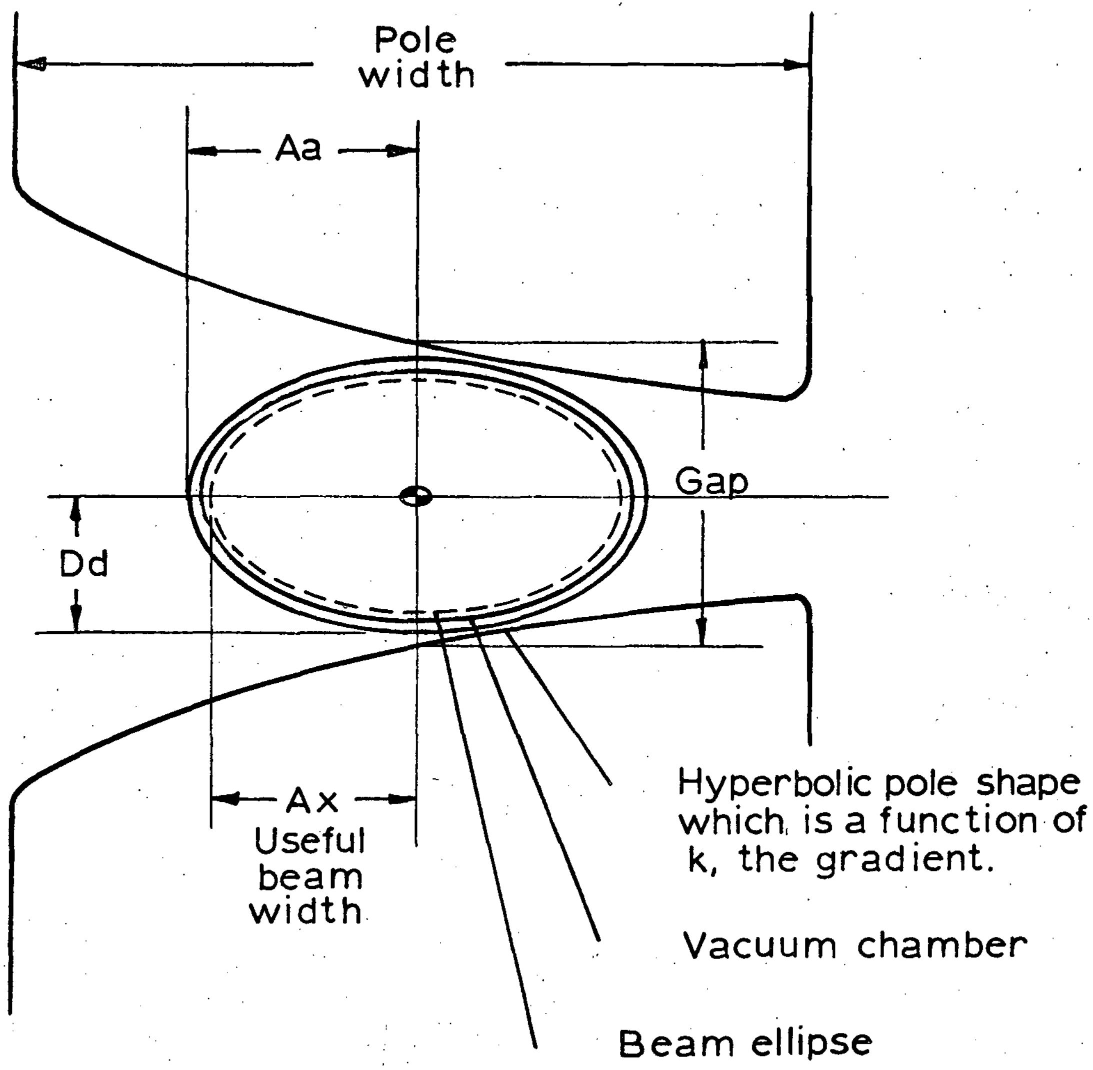
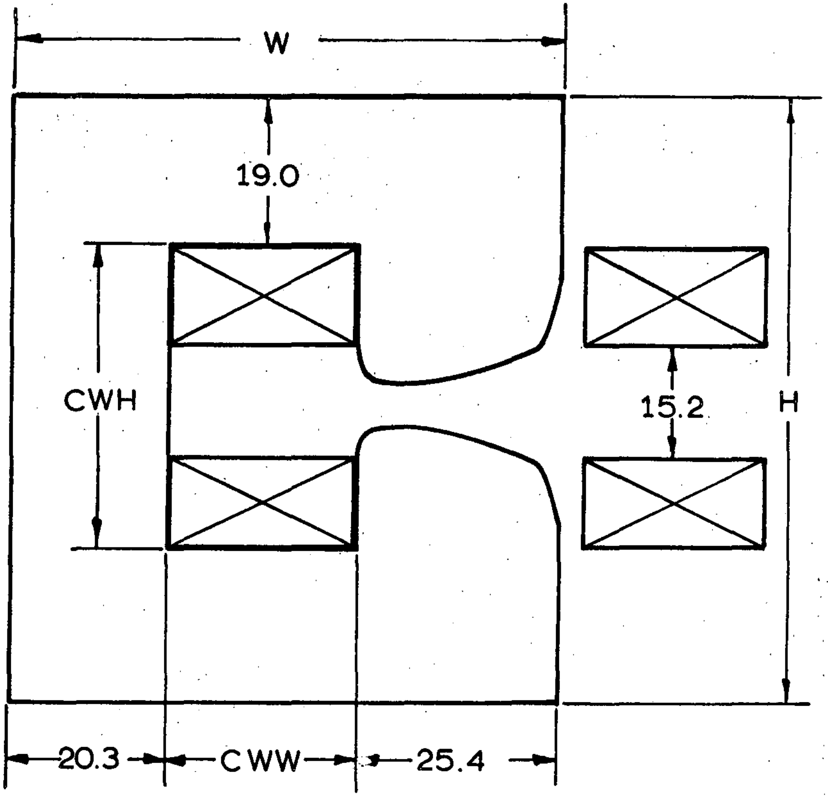


Fig. 1.

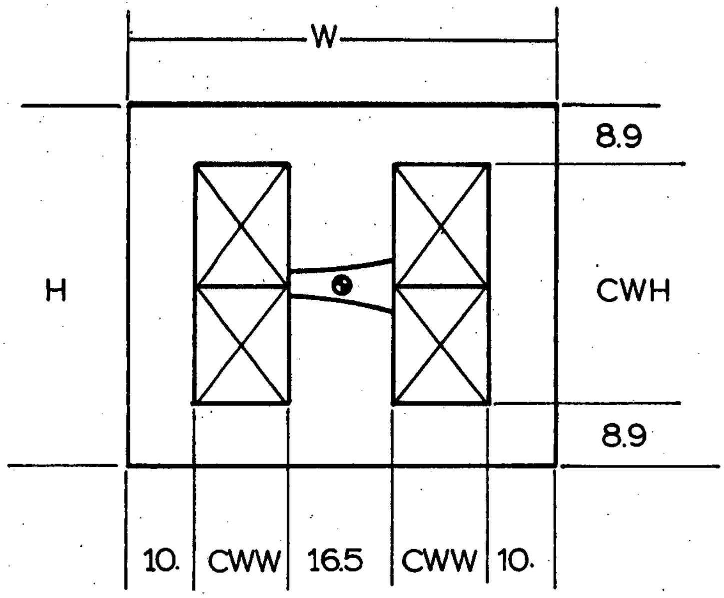
XBL 676 2052



	W	H	CWW	CWH
Copper coils	64.5	71.5	18.7	33.4
Aluminum coils	74.1	80.6	28.3	42.6

All dimensions are in centimeters

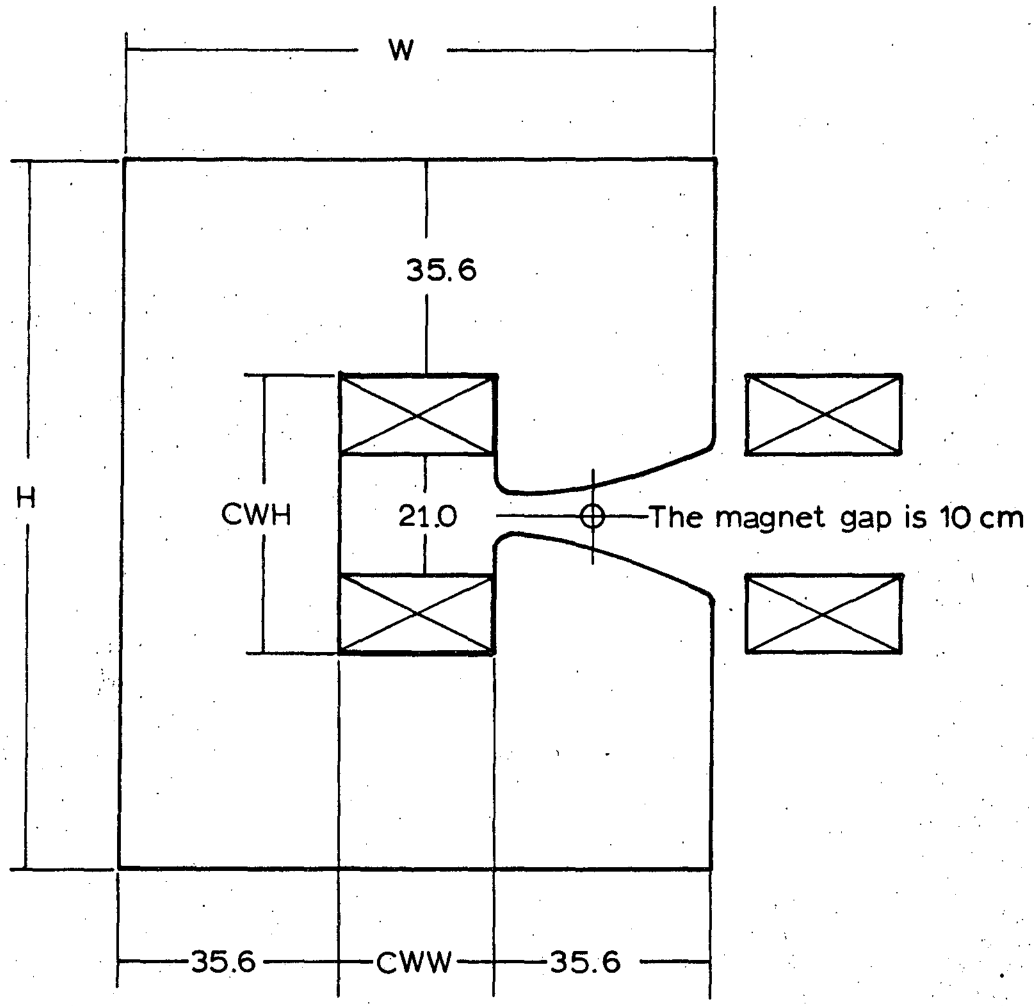
Fig. 2. XBL676 2053



	W	H	CWW	CWH
Copper coils	57.1	43.0	10.2	25.2
Aluminum coils	67.9	56.0	15.5	38.4

All dimensions are in centimeters

Fig. 3. XBL 676 2055



	W	H	CWW	CWH
Copper coils	94.2	116.7	23.2	43.6
Aluminum coils	105.6	125.8	34.4	54.6

All dimensions are in centimeters.

Fig. 4.

XBL676 2054

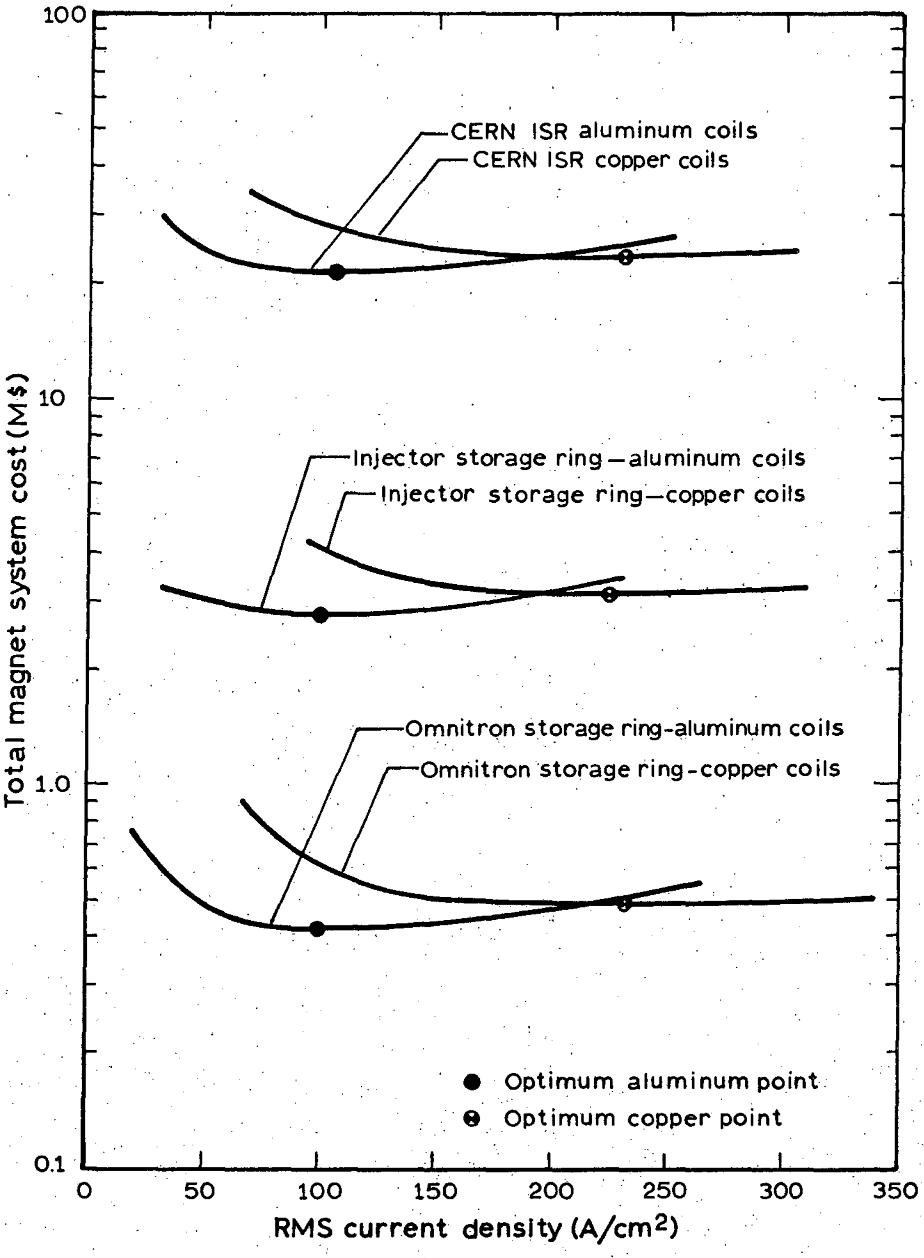


Fig. 5. XBL676 2056