Proceedings of Sector-Focused Cyclotrons, Sea Island, Georgia, USA, 1959

The Berkeley 88-Inch Cyclotron Magnet

C. G. Dols

I intend to cover a little more material than is indicated by the title; I will discuss some full-scale magnet problems, and describe some of our procedures and results.

Magnet Optimization. The first three figures show results of an optimization study made by Richard Burleigh. He made a fortunate selection of initial parameters: 3,000 amp/in.^{2} in the conductors and a return-path-area-to-core-area ratio of 1. On that basis he computed the magnet cost as a function of average flux density. As you see (Fig. 87), the optimum is fairly broad, and for the machine we were planning then, minimum cost corresponded to average flux density of 17 kilogauss. At that time we were planning to build a 50-Mev deuteron machine with a 6-in. gap. Both of these numbers have since been modified. The plan now is for a 60-Mev deuteron machine with a 7-in. minimum gap. Figure 88 shows magnet cost as a function of current density, and indicates that the choice of 3,000 amp/in.^{2} is good. Figure 89 shows the cost as a function of the ratio of return-path area to core cross section, and justifies the original assumption of a 1:1 ratio. Although the computed cost is lower for less return-path iron, it is easy to justify the 1:1 ratio for the advantages of lower stray field and rigid mechanical structure.

Model Magnet. On the basis of the optimization studies, we proceeded with the construction of the return path, core, and coils of a model (Fig. 90). The work up to this point had been guided by the reports of Dr. Stahelin [1,2]. While the model was being built we made some "pre-model tests". These tests were similar to those that Dr. King described yesterday. We put pairs of rectangular pieces of iron in a parallel magnet gap and measured the flux density between them. By the time we had completed those tests we had a copy of P. F. Smith's report[3] of the Harwell studies and found the agreement excellent. We then proceeded with confidence to design the pole tip for the magnet.

The model is 1/5 scale with a pole diameter of 17.6 inches. The size was selected to allow space in the gap for model trim coils and the polar coordinate gear. The cost increases rapidly with size for scale factors less than 1/5 and this model seems to balance such factors as cost, fabrication time, and position resolution. This model cost about $6000 and the polar coordinate gear shown about $2000.

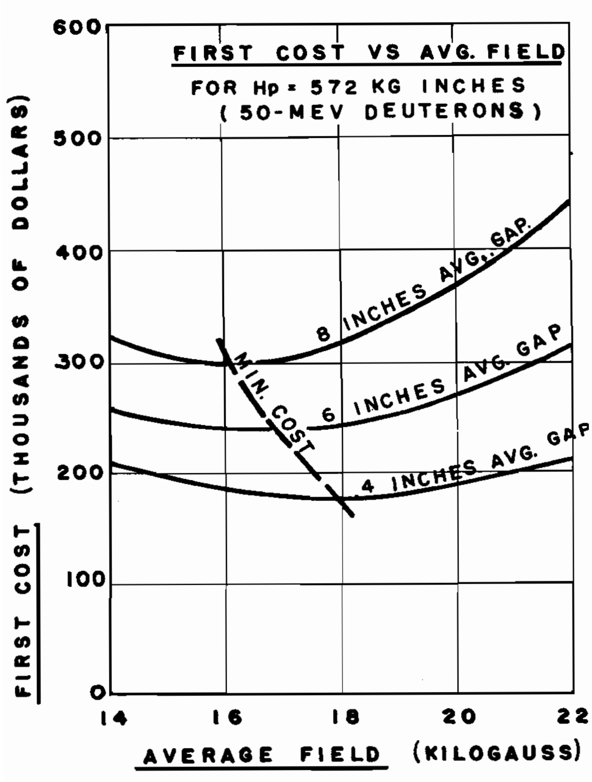

Fig. 87. Magnet cost vs average field.

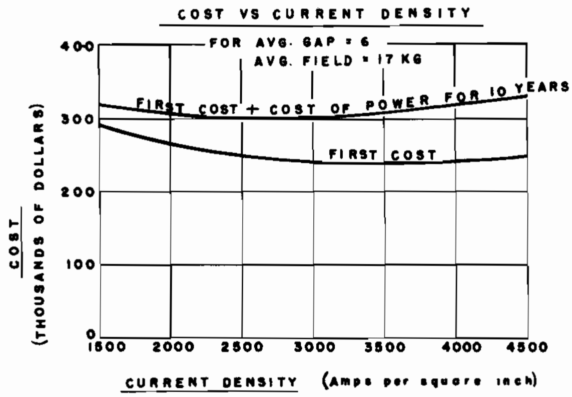

Fig. 88. Magnet cost vs current density.

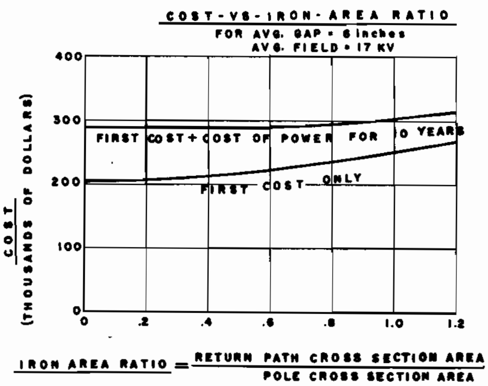

Fig. 89. Magnet cost vs amount of iron.

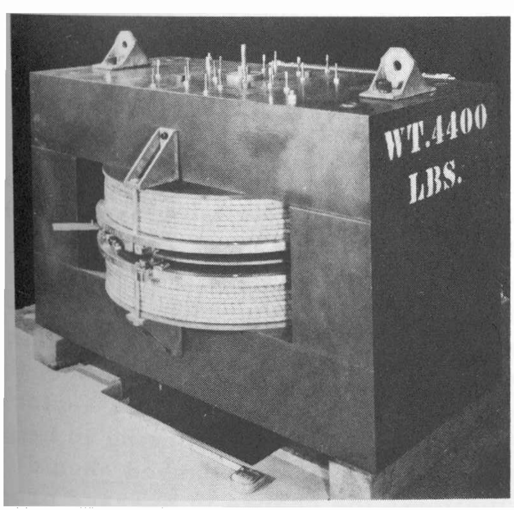

Fig. 90. The Berkeley 1/5 scale of model.

Magnetic Measurements. In Figure 91, the top of the magnet has been removed and we are looking down on the lower tip which is covered by the polar co-ordinate measuring gear. A lead screw moves a temperature-regulated bismuth resistor in the radial direction and a pawl-and-lever arrangement moves the plate in increments which are multiples of one-half degree. The bismuth resistor(4) is one that we have been using for several years.

Figure 92 shows the bismuth resistor element. Two solenoids of bismuth wire are wound in opposite directions. The length is approximately 1/8th in., the diameter is about 90 mils. The change in resistance of the bismuth is observed on a precision resistance recorder which has a resolution of 0.001 ohm in a range of 0 to 100 ohms. The output of the recorder is converted to digital form and the magnitude of resistance is punched into IBM cards, along with radial and azimuthal position numbers.

We started out, emphasizing 4-sector geometry. Figure 93 shows our first choice of sector iron. Figure 94 is a printout of raw data, showing radial positions, the resistance of the bismuth, azimuthal position, coding information, and the sequence number of the card.

At present, a complete field map for orbit calculations consists of about 1600 flux density numbers from 40 radial positions at each of 40 azimuths (in a 120° sector). In a good day of operation, the magnet group turns out one set. Joe Dorst, who is in charge of the group, told me that he has turned out as many as 2500 cards, that is, 2500 points in a day. Between the time that the raw data for one field map is on cards and the time than an error-free summary is complete, two days have elapsed. The elimination of errors is a very important step and requires unusually careful work by the magnet group.

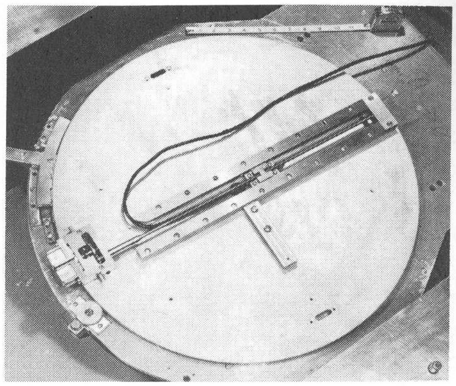

Fig. 91. Polar-coordinate probe-positioning gear.

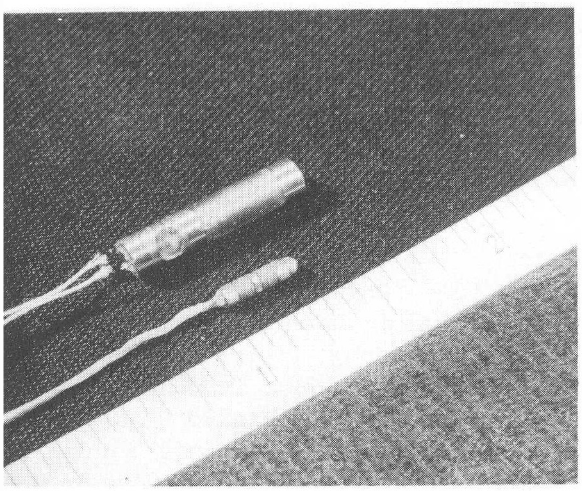

Fig. 92. Probe heater and bismuth resistor.

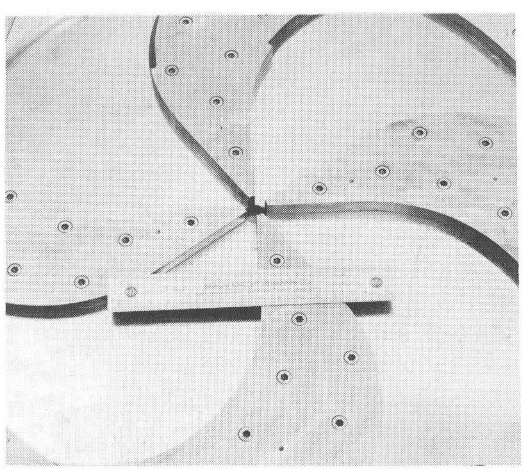

Fig. 93. Model four-sector spiral pole tip.

Fig. 93. Model four-sector spiral pole tip.

The summary sheet (Fig. 95) includes intermediate numbers which are used for getting a flutter factor, ($F^2 + 1$), radial position in 1/100 in., azimuthal average flux density, and average flux density normalized to the value at 4 inches. The data used in orbit calculations are punched in IBM cards, one card for each point.

Figure 96 is a representation of 1720 points for one value of current in the model magnet. The flux density is given as a function of azimuthal position at each of 43 radial positions. At the even inches the lines are emphasized. The intent of this figure is not to show details but to show the pattern formed by 1720 points.

Radial Profile Shaping. Yesterday Dr. Allen showed curves of average radial profile for his magnet. Figure 97 has similarly shaped curves from the 88-in. model magnet with an interesting difference. Dr. Allen's radial profiles developed a "pedestal", i.e., the field at the center increased faster than the field at larger radii when the magnet current was increased. The 88-in. model has a pedestal at low fields which decreases in prominence as magnet current is increased.

The 88-in. model magnet and the Illinois magnet have central iron configurations at opposite extremes. The 88-in. model has sectors almost all the way to the center. The Illinois magnet sectors terminate on a comparatively large flat disk at the center of the magnet. It would seem then that a compromise shape such as sectors (with beveled edges) tapering in height as the center is approached should minimize the change in average profile between low and high fields and also preserve some flutter magnitude at small radii.

The way we hope to convert this rather strange looking shape into a suitable field is by the use of a

	10000+	32401+					
		357410	120000000-	4	12	0983	1
20		357530	120000000-	4	12	0983	2
40		357940	120000000-	4	12	0983	3
60		358580	120000000-	4	12	0983	4
80		359290	120000000-	4	12	0983	5
100		359950	120000000-	4	12	0983	6
120		360520	120000000-	4	12	0933	7
140		360990	120000000-	4	12	0983	8
160		361370	120000000-	4	12	0983	9
180		361700	120000000-	4	12	0983	10
200		361940	120000000-	4	12	0983	11
220		362150	120000000-	4	12	0983	12
240		362310	120000000-	4	12	0983	13
260		362450	120000000-	4	12	0983	14
280		362510	120000000-	4	12	0983	15
300		362510	120000000-	4	12	0983	16
320		362440	120000000-	4	12	0983	17
340		362270	120000000-	4	12	0983	18
360		362000	120000000-	4	12	0983	19
380		361620	120000000-	4	12	0983	20
400		361060	120000000-	4	12	0983	21
420		360350	120000000-	4	12	0983	22
440		359390	120000000-	4	12	0983	23
460		358230	120000000-	4	12	0983	24
480		356850	120000000-	4	12	0983	25
500		355300	120000000-	4	12	0983	26
520		353700	120000000-	4	12	0983	27
540		352070	120000000-	4	12	0983	28
560		350550	120000000-	4	12	0983	29
580		349190	120000000-	4	12	0983	30
600		348070	120000000-	4	12	0983	31
620		347170	120000000-	4	12	0983	32
640		346490	120000000-	4	12	0983	33
660		346020	120000000-	4	12	0983	34
680		345710	120000000-	4	12	0983	35
700		345560	120000000-	4	12	0983	36
720		345540	120000000-	4	12	0983	37
740		345580	120000000-	4	12	0983	38
760		345630	120000000-	4	12	0983	39
780		345580	120000000-	4	12	0983	40
800		345210	120000000-	4	12	0983	41
820		344430	120000000-	4	12	0983	42
840		343210	120000000-	4	12	0983	43
860		341530	120000000-	4	12	0983	44
880		339470	120000000-	4	12	0983	45
900		337220	120000000-	4	12	0933	46

Fig. 94. Magnetic measurement raw data.

	10000	32401					
VALLEY RUNS 982	PLATE THRU 991	SOLID 3-LOBE	SECTOR 1 NEW COIL	POSITION	160 AMPS	SUM	
	9820-						25
(AVB) SQ	SUM BSQ	(BSQ) AV	N SUM B	F SQ + 1	RADIUS	AVERAGE B	RAT 25
33028	330269	33026	1000057469	99993		5747	105779425
33086	330891	33089	1000057523	100009	20	5752	105871525
33132	331348	33134	1000057560	100006	40	5756	105945125
33017	330364	33036	1000057459	100057	60	5746	105761025
32730	327908	32790	1000057206	100183	80	5721	105300925
32296	324371	32437	1000056833	100436	100	5683	104601525
31855	320804	32080	1000056441	100706	120	5644	103883625
31416	317344	31734	1000056050	101012	140	5605	103165825
31014	314164	31416	1000055685	101296	160	5569	102503225
30647	311416	31141	1000055362	101611	180	5536	101895825
30349	309090	30909	1000055087	101845	200	5509	101398825
30096	307220	30722	1000054858	102080	220	5486	100975525
29910	305916	30591	1000054685	102276	240	5469	100662625
29768	305075	30507	1000054560	102482	260	5456	100423325
29659	304478	30447	1000054463	102656	280	5446	100239225
29594	304195	30419	1000054399	102787	300	5440	100128825
29550	304111	30411	1000054357	102913	320	5436	100055225
29517	304181	30418	1000054333	103052	340	5433	100000025
29507	304322	30432	1000054318	103134	360	5432	99981525
29507	304619	30461	1000054319	103233	380	5432	99981525
29517	304957	30495	1000054328	103313	400	5433	100000025
29539	305383	30538	1000054349	103381	420	5435	100036825
29561	305778	30577	1000054374	103436	440	5437	100073625
29583	306056	30605	1000054392	103454	460	5439	100110425
29615	306420	30642	1000054422	103467	480	5442	100165625
29659	306899	30689	1000054462	103472	500	5446	100239225
29724	307633	30763	1000054523	103495	520	5452	100349725
29812	308595	30859	1000054600	103512	540	5460	100496925
29921	309842	30984	1000054700	103552	560	5470	100681025
30030	311054	31105	1000054803	103579	530	5480	100865025
30173	312410	31241	1000054933	103539	600	5493	101104325
30305	313551	31355	1000055051	103464	620	5505	101325225
30459	314863	31486	1000055191	103371	640	5519	101582925
30636	316472	31647	1000055350	103300	660	5535	101877425
30836	318424	31842	1000055534	103262	680	5553	102208725
31103	320918	32091	1000055767	103176	700	5577	102650425
31394	323700	32370	1000056027	103108	720	5603	103129025
31697	326555	32655	1000056296	103022	740	5630	103625925
31843	327855	32785	1000056434	102958	760	5643	103865225
31641	325392	32539	1000056251	102838	780	5625	103533925
30747	315844	31584	1000055453	102722	800	5545	102061425
28869	296031	29603	1000053732	102542	820	5373	98895625
25786	263599	26359	1000050783	102222	840	5078	93465825
21762	221507	22150	1000046650	101782	860	4665	85864125

Fig. 95. Magnetic measurement processed data summary.

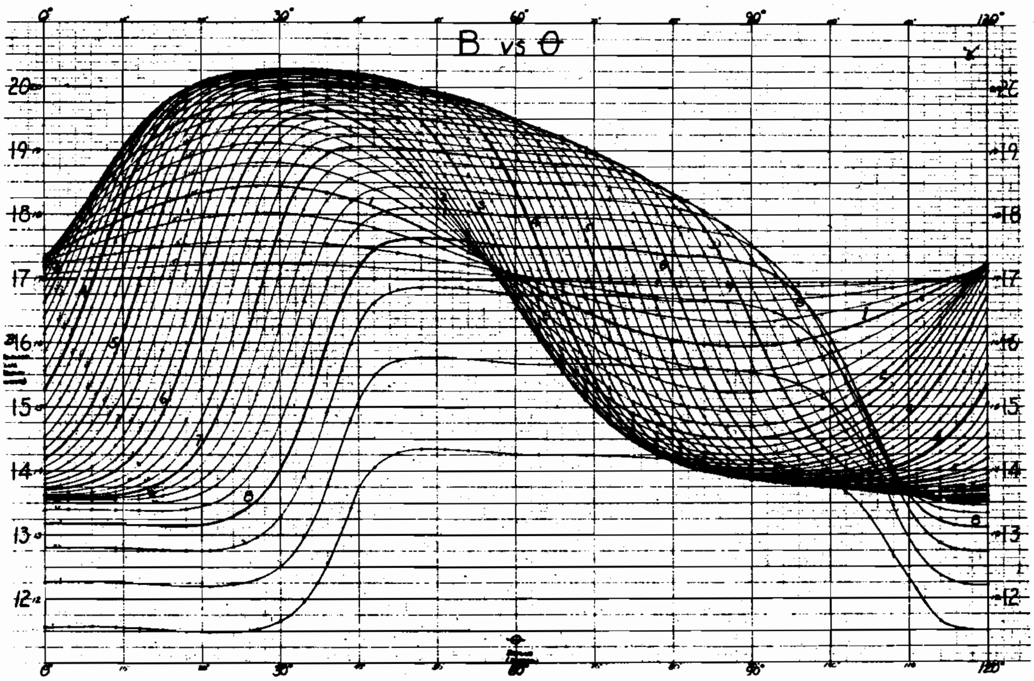

Fig. 96. Example of flux density as a function of azimuthal position.

combination of holes in the iron and with circular trimming coils. We spent some time in the early stages of our program attempting to avoid trimming coils almost entirely, at least to have no trimming coils to correct the radial profile. We hoped to do it with moving rods of iron. We found that it is quite difficult to compensate over even a small range with any reasonable configuration of iron and gaps. The forces on the rods, for example, make the mechanical problem quite difficult. At that time we were concerned about the reliability of trimming coils, expecting that they would become radioactive and be very difficult to repair. We tried to work out a plan using moving rods outside the vacuum away from the gap. We next played with the idea of circular coils, again outside the vacuum system in a special plate, well away from the gap. At the time we tested rectangular pieces of iron we also tested the effect of conductors below the iron surface. While they gave a rather satisfactory change in the magnitude of the flux density, their maximum gradient effect -- in other words, their ability to twist the shape of the field directly above the conductor was less than half of what we had hoped for. We felt then

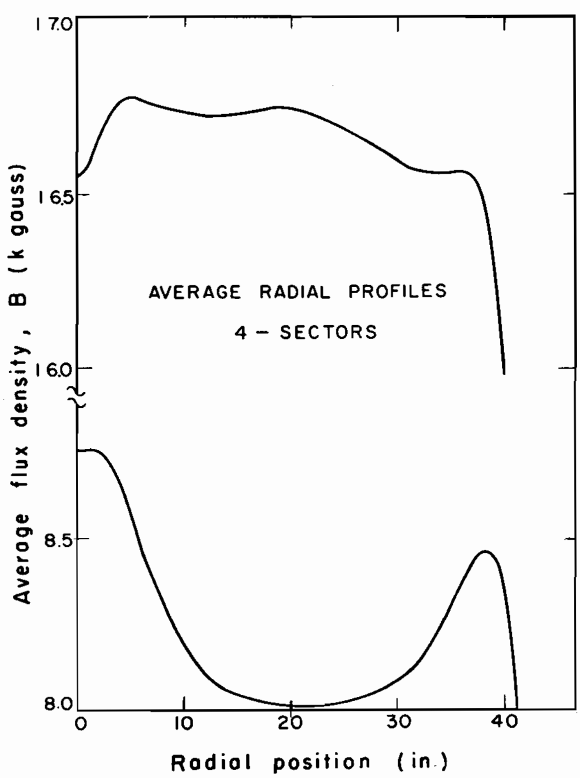

Fig. 97. Four-sector geometry average radial profiles.

that we would be forced to use trim coils in the gap, and fortunately Dick Burleigh suggested a design which is generally accepted as being sufficiently reliable. I would like to ask Dick, who has some pieces of costume jewelry with him, to describe these trim coils.

BURLEIGH: I do just happen to have a sample with me [laughter]. This is really not a new idea; in fact; it is a kind of cable that was invented in France, and it turns out it is the only kind of cable that the French will allow in the Louvre. It is a fireproof cable. What it consists of is a copper tube with a copper rod in the center and the rod is surrounded by magnesium oxide. It is rather interesting the way they make this. They start with a large pipe and large rod, pack in the powder, and then draw the whole thing. In fact, they can draw four conductors together and not have them touch.

The scheme is to solder this mineral-insulated conductor (made by General Cable Corporation), to a 1/8 in. copper sheet which forms the base for the coil and also serves as r-f liner. Then to the same sheet we would also solder cooling tubes. This scheme is not exactly new. It was used on the Livermore machine, although I guess it didn't play double duty as also the r-f shield.

While we are passing the hardware around there is also another little item on dees. I know this has nothing to do with the discussion at the moment but I might as well disturb the group just once. This is a possible construction for a dee. The design is always squeezed in thickness. This is a scheme which involves manufactured items, commercial materials, one of which is stainless steel clad with copper and the other is a dimpled stainless steel sheet which is known as "All-Stresst." I sound a little commercial here. This is what we propose to do then: Say, we are talking about the top layer of the dee; we will have this copperclad stainless steel, of course, on top and then the sandwich composed of this dimpled layer of stainless steel with the other layer of stainless steel underneath, and these will be spotwelded together. You have to introduce the other layer of stainless steel underneath the copper because you cannot spot-weld to copper very satisfactorily. At the same time we will also spot-weld on a strip of the same copper-stainless material to which has been soldered a cooling tube. Holes are provided on the underside of the lower sheet to serve the double purpose of pump-out and also as access to insert the welding electrode.

DOLS: Figure 98 is a photograph showing a model trimming coil assembly. The upper pole of the model and the polar coordinate gear have been removed to show the lower coils of a test assembly in position in the model. The test assembly includes two pairs of coils, one pair of 3 in. dia and the other about 15 inches. The effects of these coils have been studied by looking at changes in average radial profiles. For the range of currents we expect to use the effect of a trimming coil pair is linear with trimming coil current. For fixed trimming-coil current the change in radial profile at an average field of 8 kilogauss is about 150% of the effect at 17 kilogauss. The magnitudes and shapes of the effects of the 3-in. and the 15-in. coils are almost identical except that the larger coil has an understandably larger effect on the over-all average flux density level.

Figure 99 shows the lower pole of the model with a three-sector poletip assembly in position. Note the separable sector parts in the central region and the beveled edges. The removable center parts are convenient for developing shapes that reduce the magnitude of the "pedestal" problem. Beveled edges are effective in

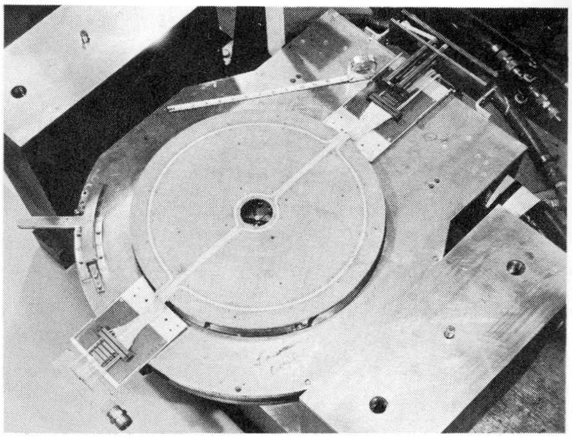

Fig. 98. Model trimming coils.

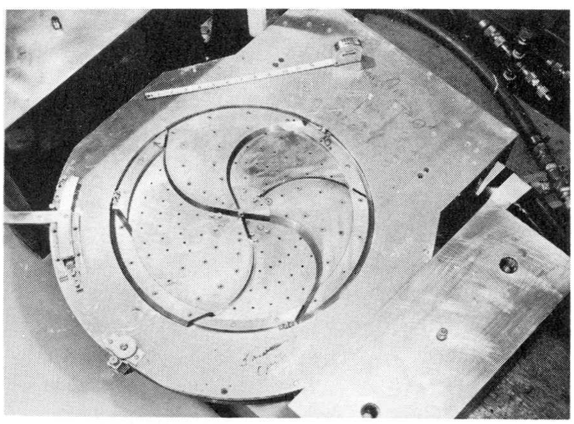

Fig. 99. Three-sector model pole tip.

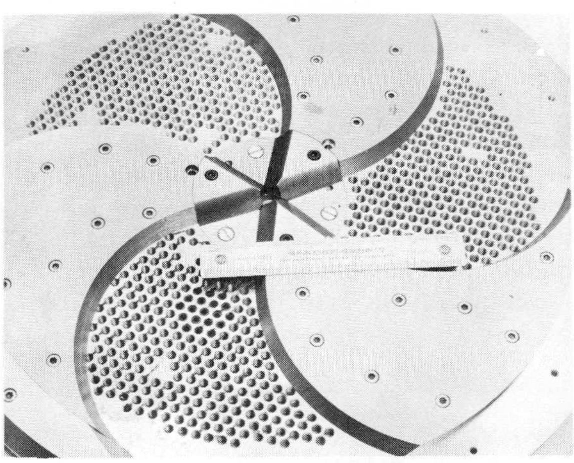

Fig. 100. Model pole tip showing valley surface voids.

controlling changes in shape of average radial profile as field level is varied.

We intend to compensate changes in shape of the radial profiles with a combination of trim coils and voids. We have two kinds of voids. To get fairly sharp gradient effects we expect to use holes in the surface of the valleys as shown in Figure 100. An example of the other kind of void is shown in Figure 101; the hills and the valley plate with the holes have been removed to expose a series of concentric rings which is the test fixture for measuring the effect of holes below the pole-tip surface. In this photograph the rings between 3 and 5-in. radius have been removed. The effect of removing these rings is to cause saturation in the intermediate radial positions and thus introduce a compensating negative pedestal which is intended to balance the central and the outside in the radial profile shape.

Azimuthal Average Search Coil System. Our measuring program has separated into two patterns. We need data for orbit plotting and we also need data to develop the means for correcting the average radial profile. These requirements are more or less independent. Originally we took 1600 points (sometimes about 500 points) to get an average radial profile. This is tedious. A device for obtaining average radial profile information with less work is almost ready to use.

Reference 5 describes a system for obtaining the azimuthal average of the flux density at a series of radial positions. Figure 102 shows the search coil assembly for the system. The plate shown has about 50 concentric coils. Each coil is connected in opposition to an adjacent coil and each coil of the pair has exactly as many turns as its mate. A coil pair thus responds only to the change in flux density in the annulus between the coils. If the area of a coil pair is adjusted to be exactly equal to the area of another coil par, and the coil pairs are connected in opposition the output of the combination is proportional to the incremental difference in the average radial profile between the corresponding radial positions i.e., between a reference and any other radius. The output of the coils is fed into an electronic integrator. The integrated voltage is measured with a self-balancing strip chart recorder. In order to get a reproducible change in flux density the magnet current is reversed. Bob Smith has constructed a device for quickly reversing the magnet current, and in about 15 seconds 99.99% of the final flux change has been completed. Figure 102 also shows the switch panel which permits selecting any coil as a reference and connecting any other coil in opposition to it.

The coil pairs are standardized in effective area by adjusting the ten-turn potentiometers shown in Figure 103. The calibrated dials permit rapid initial adjustments. Figure 104 is a closeup of the search coil plate. Each coil (of 50 to 75 turns) is wound on 24 insulated brass nails in the bakelite base.

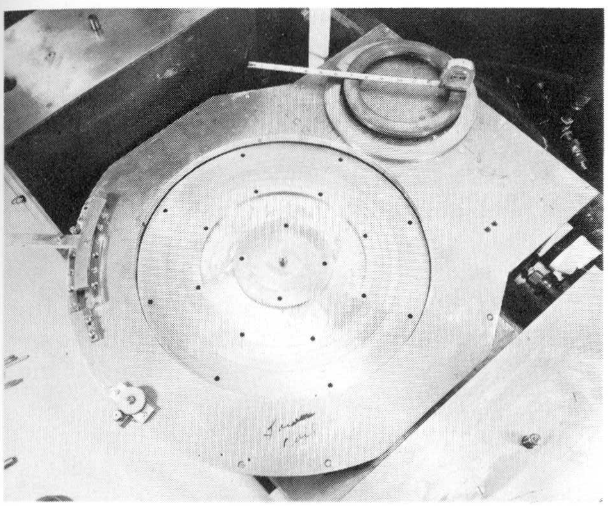

Fig. 101. Model of sub-surface voids.

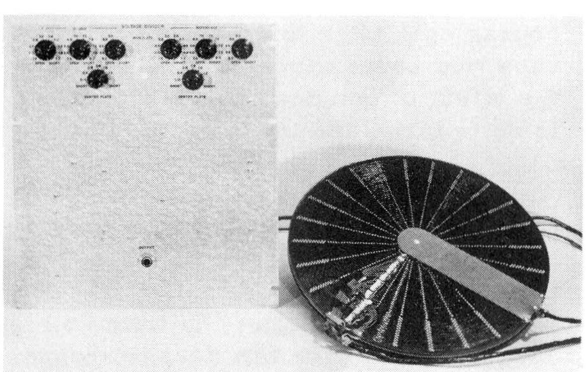

Fig. 102. Search coil plate and selector panel.

Effect of Magnet Coil Position. As the design of the 88-in. magnet developed it became possible to move the coils closer together. Figure 105 displays average radial profiles for 3-sector geometry and the effect of moving the coils. The change from 25 in. between coils to 15 in. permitted a reduction in current and improved the shape of the radial profile. At low fields the two curves are almost identical. Figure 106 and 107 show how the two coil positions were modeled. In order to move the coils together, the probe positioning equipment was redesigned.

In conclusion: We are quite confident that the present trimming coil and void design will compensate the expected changes in the radial profile. We have yet to complete a plan for controlling first and second harmonics.

BOYER: I would like to make one comment on the coils. We have a set of correcting coils which are insulated with a 10-mil layer of fiberglass and epoxy resin. These have been running three or four years now, something like that, and there has never been any trouble with them. They are in the vacuum tank behind the 1/8-in. copper liner. These coils lead up and down over the Thomas shims, and whence they cross over they are protected with only a 20-mil copper layer; they

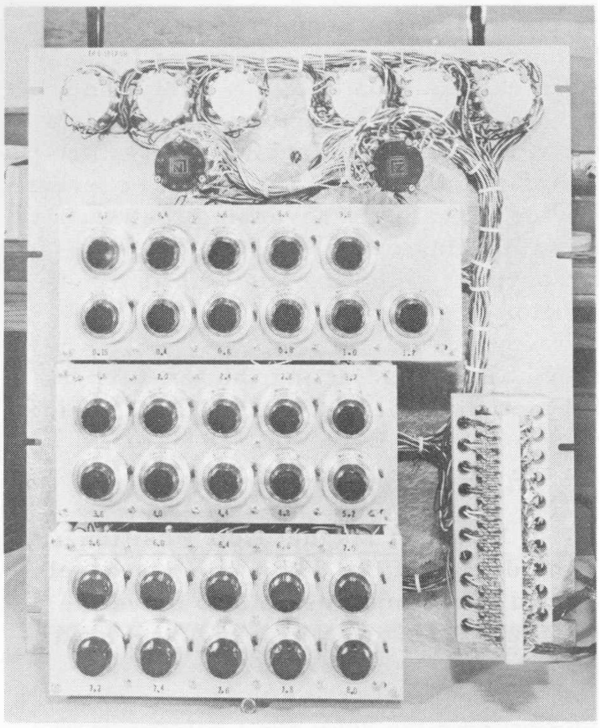

Fig. 103. Rear view of selector panel.

Fig. 104. Close-up view of search coil plate.

certainly have been subjected to a great deal of radiation and so far no trouble of any kind has developed. I think it would indicate you can get by with more than you might at first suspect.

POWELL: I'll make just one comment on the use of mineral insulated cable. We are planning to use this cable, too, and we are thinking of going to a rather small diameter, about 0.050 on the sheath. This means that the conductor is about 1/32 in. dia and we can run it at about 9 amps. The advantage of this is that we can easily bring our controls out to the control room on about 30 separate coils. Are you planning to use the size of cable you passed around or are you thinking about drawing it down to a smaller diameter?

BURLEIGH: The sample being passed around is not the size we plan to use; it is a smaller size.

BOYER: Have you investigated the effect of leaving a thin air gap underneath the plate on this saturation in the center. We have observed that in running at from 2 to almost 19 kilogauss and there is very little change in this; the only difference I can see is that there is an air gap between the poleface and the tip which might tend to redistribute the flux again.

DOLS: Unfortunately, I don't have a slide, but our test data is quite encouraging. After this session I can show you some curves that illustrate the effect of our deep hole. The effect is quite large and looks good.

Dr. Powell's question reminded me of Konrad's paper(6) on ion phase measurements in the Birmingham cyclotron which is significant in relation to the problem of adjusting trim coil currents. We have felt uneasy about the problems the operator will face when tuning the cyclotron, since changing the current in any trim coil changes

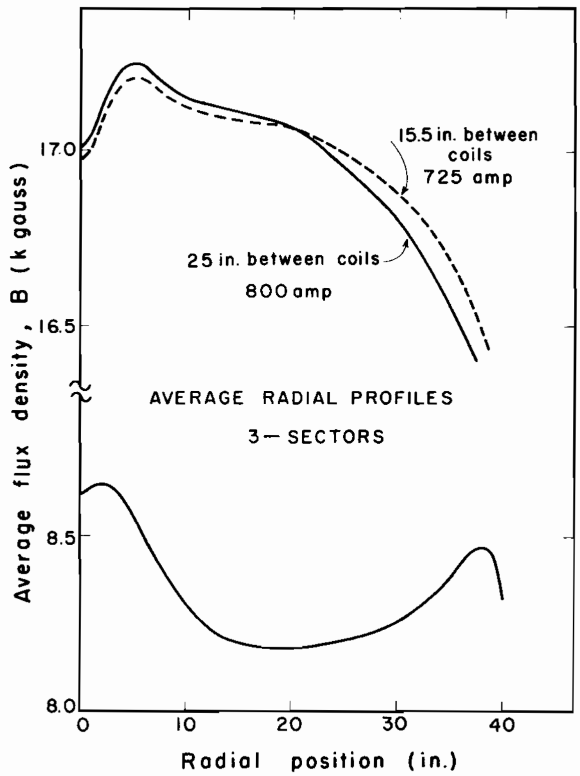

Fig. 105. Three-sector average radial profiles.

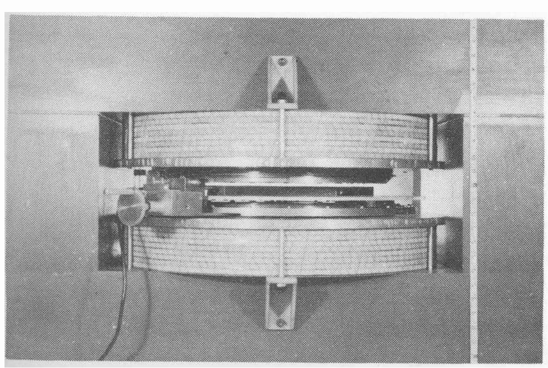

Fig. 106. Front view of the model magnet.

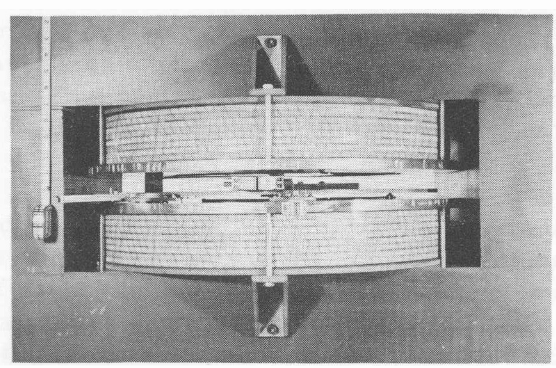

Fig. 107. Front view of the model magnet after reducing the coil separation.

the lux throughout the gap. It has been suggested that this problem be handled by a computer program. Whenever an open loop procedure begins to look involved we electrical engineers try to apply a closed loop. In this case it would seem that a closed loop might include the operator who would look at a display of the difference of the phase of the ions and r-f phase. On the basis of Konrad's report it would seem to be possible to run a probe in and out along a radial line and pick up ion phase information. The phase could be displayed as a function of radius and the operator would have an "instantaneous" indication of the effect of a change in trim coils current at all radii.

KING: I would like to inquire about the minimum gap you can use to accommodate your positioning gear.

DOLS: Well, we could operate in 1 inch, the problem being that the positioning gear must be almost entirely on one side of the midplane. The apparatus that Dr. Snowden described yesterday is much more economical of gap space.

References

(1) Peter Stahelin, The Radial Stability of Orbits in a Spiral Ridge Cyclotron, Technical Report No. 1, Office of Naval Research Contract Nonr 1834 (05) Physics Department, University of Illinois.

(2) V. Bluemel, J. B. Carroll, and P. Stahelin, Investigation of the Field Modulation Produced by Flat Spiral Shims in a Cyclotron Magnet, Technical Report No. 2, Office of Naval Research Contract Nonr 1834 (05), Physics Department, University of Illinois.

(3) P. F. Smith, Further Measurements of the Magnetic Field Produced by Ridged Pole Pieces, A.E.R.E. A/R 2514, U.K.A.E.A. Research Group, Atomic Energy Research Establishment, Harwell.

(4) C. G. Dols, E. W. Skiff, and P. G. Watson, Temperature-Regulated Bismuth Resistor for Magnetic Field Measurements, Rev. Sci. Inst. 29, 5 349-54 (May, 1958).

(5) C. G. Dols, 88" Cyclotron Model, Magnetic Measurements System, Azimuthal Average Integrator, Lawrence Radiation Laboratory, Berkeley California, Informal Report No. UCID-624.

(6) M. Konrad, Ion Phase Measurements on the Birmingham Cyclotron, Rev. Sci. Inst. 29, 10, p 840 (October, 1958).