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BEAM DIRECTOR DESIGN REPORT

AUGUST 1986

VOLUME I

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TABLE OF CONTENTS - VOLUME I

	<u>PAGE</u>
ABSTRACT	viii
ACKNOWLEDGEMENTS	ix
1.0 EXECUTIVE SUMMARY	1-1
2.0 STATEMENT OF REQUIREMENTS	2-1
3.0 DESIGN SUMMARY	3-1
4.0 PHOTOGRAPHS	4-1
5.0 ANALYSIS AND COMPUTATION	5-1
5.1 ACHROMAT	5-1
5.1.a Steering and Focusing	5-1
5.1.b Magnetic Field Calculations	5-5
5.1.c Sorting of Magnetic Segments	5-8
5.1.d Trim Coils for Achromat	5-10
5.2 VERNIER	5-13
6.0 MATERIALS	6-1
7.0 MANUFACTURING	7-1
7.1 ACHROMAT	7-1
7.1.a Procurement and Fabrication	7-1
7.1.b Magnetic Measurements	7-2
7.1.c Assembly	7-3
7.1.d Testing	7-3
7.2 VERNIER	7-4
7.2.a Procurement and Fabrication	7-4
7.2.b Assembly	7-5
7.2.c Magnetic Measurements	7-5
7.2.d Testing	7-5

TABLE OF CONTENTS - VOLUME I (continued)

	<u>PAGE</u>
8.0 ASSEMBLY DRAWINGS: ACHROMAT	8-1
9.0 ASSEMBLY DRAWINGS: VERNIER	9-1
10.0 PROJECT FUNDING	10-1
11.0 REFERENCES AND BIBLIOGRAPHY	11-1

TABLE OF CONTENTS - VOLUME II

A. Funding Instruments	A-1
B. Requests for Quotations (RFQ's)	B-1
C. Purchase Orders	C-1
D. Drawings: Achromat	D-1
E. Drawings: Vernier	E-1
F. Magnetic Measurements Reports, Lawrence Berkeley Laboratory	F-1
G. Conceptual Design of an Electron Beam Deflector	G-1
H. Beam Director Components for ATA Tests (Final Report)	H-1

LIST OF FIGURES

	<u>PAGE</u>
1-1. Conceptual Design of the Beam Director	1-4
3-1. Magnetic Lattice Showing the Arrangement of Quadrupoles and Bending Magnets (Dipoles)	3-4
3-2. Permanent Magnet Dipole	3-5
3-3. Permanent Magnet Quadrupole	3-6
5-1. First-Order Wedge Dipole Matrix	5-19
5-2. First-Order Quadrupole Matrix	5-20
5-3. Single "FOODOF" Cell from Multi-Cell Achromat	5-21
5-4. Beam Trajectories through Achromat -- Off Axis, On Angle	5-22
5-5. Beam Trajectories through Achromat -- Off Angle, On Axis	5-23
5-6. Beam Trajectories through Achromat -- Off Energy 2%	5-24
5-7. Beam Trajectories through Achromat -- Off Energy 2%, Gradient Error 2%	5-25
5-8. Permanent Magnet Segment Arrangement, Dipole Field	5-26
5-9. Permanent Magnet Segment Arrangement, Quadrupole Field	5-27
5-10. Permanent Magnet Segment Arrangement, Quadrupole Field, with Segments Specified	5-28
5-11. Sample Shop Sketch for Magnet Assembly	5-29
5-12. Vernier Coil Positions for Calculation of Field	5-30
5-13. Plot of Relative Field Values at a One cm Radius	5-31
6-1. Ferrimag 7B Demagnetization Curve and Energy Product Values	6-3
7-1. Manufacturing Time-Line	7-6

LIST OF TABLES

	<u>PAGE</u>
3-1. Achromat Characteristics	3-3
3-2. Beam Path Through Achromat with Shown Elements	3-7
3-3. Permanent Magnet Dipoles	3-8
3-4. Quadrupole Assemblies Measurements Summarization	3-9
3-5. Vernier Characteristics	3-10
3-6. Power Supplies and Expected Fields for Beam Director Components	3-11
5-1. Beam Path Through Achromat -- Off Axis, On Angle	5-32
5-2. Beam Path Through Achromat -- Off Angle, On Axis	5-33
5-3. Beam Path Through Achromat -- Off Energy 2%	5-34
5-4. Beam Path Through Achromat -- Off Energy 2%, Gradient Error 2%	5-35
5-5. Achromat Characteristics	5-36
5-6. Sample of Magnetic Measurements Received from Lawrence Berkeley Laboratory	5-37
5-7. Spreadsheet Computation of Magnetic Fields Due to Trim Coils	5-38
5-8. Vernier Coil Positions	5-39
5-9. Calculation of Fields for Vernier Coils at Center, 0° Angle	5-40
5-10. Calculation of Fields for Vernier Coils at 1 cm, 0° Angle	5-41
5-11. Calculation of Fields for Vernier Coils at 1 cm, 30° Angle	5-42
5-12. Calculation of Fields for Vernier Coils at 1 cm, 60° Angle	5-43
5-13. Calculation of Fields for Vernier Coils at 1 cm, 90° Angle	5-44
6-1. Ferrimag 7B Technical Data	6-2
6-2. Achromat Materials	6-4
6-3. Vernier Materials	6-5
7-1. Achromat Purchase Order List	7-7

LIST OF TABLES (continued)

	<u>PAGE</u>
7-2. Achromat Assembly Steps	7-8
7-3. Vernier Purchase Order List	7-11
7-4. Vernier Assembly Steps	7-12
8-1. Achromat Drawing List	8-2
9-1. Vernier Drawing List	9-2
10-1. Project Costs by Month	10-2
10-2. Man-Hour Summary	10-3

LIST OF PHOTOGRAPHS

	<u>PAGE</u>
4-1. Permanent Magnet Assembly	4-1
4-2. Partially Assembled Achromat	4-2
4-3. Assembled Achromat	4-3
4-4. Vernier Coil Material Ready to Anodize	4-4
4-5. Assembled Vernier	4-5
a. End view (downstream)	
b. End view (upstream)	
c. Side view	
4-6. Vernier Measurement Set-up	4-6
4-7. Vernier Assembly Test Mount	4-7
4-8. Achromat and Vernier Assemblies Ready to Ship	4-7
4-9. Achromat Installed for Beam Test	4-8

ABSTRACT

This two-volume design report contains detailed documentation of the Beam Director Project, a design and fabrication effort undertaken by Brobeck Corporation for the Lawrence Livermore National Laboratory (LLNL). Following an initial concept study for a beam director, a prototype permanent magnet 30° beam-bending achromat and a prototype vernier steering magnet were designed and built. Included in Volume I of this report are an executive summary, a statement of design requirements, a summary of the design, photographs, a detailed analysis and computation section, a summary of materials used, a description of the manufacturing process, as-built assembly drawings, a summary of project funding, and a list of references. Included in Volume II are copies of the funding instruments, requests for quotations, purchase orders, a complete set of as-built drawings, magnetic measurements reports, the concept design report (9/83), and the final report (12/85) on the design and fabrication project.

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Mr. Gilbert E. Cruz, Lawrence Livermore National Laboratory, was most helpful in the design, fabrication, and testing of the prototype achromat and vernier.

The Magnetic Measurements Engineering Group at Lawrence Berkeley Laboratory, in particular Mr. Donald H. Nelson and Dr. Michael I. Green, provided valuable assistance in measuring and selecting the magnet segments and in final assembly quality assurance.

I want to thank these and all the other scientists and engineers from various laboratories who participated in review meetings throughout the project and provided comments and suggestions that kept us alert to problems and to the criteria that the final device must satisfy.

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F. C. Younger, Principal Investigator

1.0 EXECUTIVE SUMMARY

In a conceptual study conducted in 1983, Brobeck Corporation designed a permanent magnet beam director to transport high energy electrons. The report on the conceptual design study is included as Appendix G, Volume II.

The conceptual design of the beam director is shown in Figure 1-1. The beam passes through the first bending and focusing system (or "achromat"), through the second achromat, through the air-to-vacuum interface (the "beam window"), and finally through the vernier steering system ("vernier").

The overall concept for the achromat was established during the conceptual design study, where it was shown that an achromatic bend could be achieved with a grouping of bending magnets (dipoles) inserted between alternately focusing and defocusing quadrupole magnets. It was also shown that the required bending magnet fields and quadrupole magnetic gradients could be obtained using permanent magnets. The use of permanent magnets makes the achromat lightweight and compact, because it is unencumbered by heavy power supplies, coils, and large cooling systems. This is especially advantageous to the beam director because it allows greater maneuverability.

Two permanent magnet 30° beam-bending achromats are the major components used for bending the electron beam. A single achromat produces an achromatic bend of a specific angle, "alpha" (in this case, 30°). By using two such achromats joined in tandem, any desired bend direction from 0° up to 2α (in this case, 60°) can be obtained.

A high degree of accuracy for the magnets is required to achieve the desired beam optics. To compensate for likely field errors and to provide

some operating flexibility, trim coils for adjusting the quadrupole gradients are installed along the outside of the achromat.

The vernier is a non-achromatic steering device used to provide a relatively small amount of fine tuning of the final bend angle. Since the bend angle is small (less than 2°), the chromatic aberration is not significant. The main concern is that the unit be lightweight, with an accurate and easily controlled magnitude and direction of bend.

For the vernier, two sets of mutually perpendicular coils in a coaxial arrangement are used. One set of coils bends the beam in the horizontal plane and the other in the vertical plane. By energizing the coils in combination, the beam can be aimed within $\pm 2^\circ$ from the major axis.

During 1984, the design work continued on the achromat, vernier, and beam window. Detailed drawings were completed, and several design reviews were held at Lawrence Livermore National Laboratory (LLNL).

In 1985, Brobeck Corporation was authorized to build a prototype achromat and a prototype vernier for verification testing at high beam currents at the Advanced Test Accelerator (ATA) at LLNL. These two components were selected for development to show that the required accuracy could be achieved and to demonstrate the beam director's effectiveness at very high currents in the special environments that could be simulated in the laboratory. (Although the beam director includes two achromats, it is only necessary to design, build, and test one achromat in order to determine feasibility). Development of the spinning disk beam window was not considered as critical as the achromat and vernier to the success of a beam director, so further work on the window was postponed.

The prototype achromat and vernier were completed in December 1985, and

a preliminary test at low current has been successfully accomplished using the RF linac at LLNL. A test at full power is planned for a later date, to be determined by the ATA operating schedule. The final report on the design-and-build project is included as Appendix H, Volume II.

Tests at the high beam currents available from the ATA will provide answers to critical questions regarding operation of beam director components at high currents where space charge and ionization problems may be present. Full testing and experimental verification of the finished components are required before undertaking the design and construction at a higher performance level.

In 1986, Brobeck Corporation was contracted to produce a design report on the beam director project. This design report documents the beam director project from concept to operating hardware. The report is in sufficient detail so that anyone familiar with magnetic beam optics could build another achromat and vernier without repeating the design work and material selection. The design documentation for these components is intended to serve as a major first step in beam director development.

FIGURE I-1. CONCEPTUAL DESIGN OF THE BEAM DIRECTOR

2.0 STATEMENT OF REQUIREMENTS

The following specifications for the achromat and vernier were developed during the conceptual design study.

ACHROMAT

The achromat contains permanent magnet dipoles and quadrupoles for bending and focusing a beam of 45 MeV electrons. The total bend angle is to be 30° and is to be made with no chromatic dispersion. A first-order achromatic bend is required. To achieve this, the betatron phase advance in the plane of the bend is to be 2π radians. The phase advance will assure that the horizontal phase space portion of the transformation matrix be an identity matrix. The vertical phase space portion will be nearly an identity matrix, but it need not be exactly so. With this overall transformation matrix, the phase space coordination of the exiting beam will be nearly identical with those of the entering beam. Because the magnetic focusing characteristics of permanent magnet quadrupoles may not prove to be exactly as desired, a set of quadrupole trim coils is provided with sufficient field adjustment to compensate for field errors and to give operational flexibility.

The overall magnetic length of the achromatic bend is 157 cm, with a clear aperture adequate to transport a beam with an initial diameter of one centimeter. The beam tube has an electrically conducting surface to carry the counter current, with an end connection to conduct the current to adjacent beam tubes without sparking. The tube and end connections are part of the vacuum system.

Cooling coils are used to maintain the achromat at a nearly constant temperature in order to avoid field changes in the permanent magnets, which

are slightly temperature sensitive. The cooling system is also used to dissipate the ohmic heating of the trim coils.

The achromat structure is lightweight, but with sufficient structural rigidity to maintain alignment of the magnetic elements. The end flanges are compatible with the tank flanges on the ATA to facilitate installation for testing.

VERNIER STEERING MAGNET

The vernier is a set of electromagnetic coils that will produce well controlled transverse magnetic fields of sufficient magnitude and direction to steer a 45 MeV electron beam to any desired direction of bend up to 2° off the achromat axis. The transverse magnetic field is produced by two sets of coils that are separately controlled in such a way as to permit easy rotation of the resultant field vector. Rotating this vector to a prescribed position will control the direction of the bend, while setting the magnitude of this vector will control the amount of the bend.

The nominal length of the vernier is 40 centimeters, with a clear aperture large enough to allow clearance for the deflected beam as well as possible beam blow-up.

The inside of the beam tube has sufficient electrical conductivity to carry the counter current induced by the beam current. There is also a conducting path at the ends of the beam to conduct this counter current to adjacent beam tubes without sparking.

The unit operates in a tank that provides control of the environment. The tank may be operated at a vacuum or with low pressure gases to investigate the problems associated with space charge and with ionization of the residual

gas. Water-cooled coils are installed to dissipate ohmic heating when operating in a vacuum. Since steady state cooling in a vacuum may be excessively difficult, it is recommended that operation be limited to short periods of time.

3.0 DESIGN SUMMARY

The achromat is designed to bend a 45 MeV electron beam 30° . The achromat uses permanent magnet dipoles and quadrupoles in a lattice structure designed to give a 360° phase advance. The characteristics for the design are listed in Table 3-1. The arrangement of the dipoles and quadrupoles is shown in Figure 3-1 and the arrangement of permanent magnet segments required to produce dipole and quadrupole fields is shown in Figures 3-2 (dipole) and 3-3 (quadrupole). The focusing characteristics (non-zero matrix elements) are shown in Table 3-2. The final design used defocusing quadrupoles in the end positions, as shown in Table 3-2; the arrangement shown in Figure 3-1 (with focusing quads at the ends) is from the preliminary concept study, as is Table 3-1.

The magnetic strength and the alignment of the permanent magnets varies slightly from segment to segment due to random errors. In order to minimize any adverse effect that variations in alignment and magnetic strength may have upon the achromat, each segment was separately measured for magnetic moment and orientation of magnetic axis. Using these measurements and a simple algorithm, the segments were sorted prior to their assembly into dipoles and quadrupoles in such a way as to minimize accumulative errors.

The assembled dipoles and quadrupoles were also measured, so that they could be positioned in the achromat in such a way as to further distribute the magnetic errors and thus minimize aberrations. The measured dipole fields shown in Table 3-3 were all slightly higher than the desired 0.1107 tesla. The maximum value was 0.1126 tesla and the minimum was 0.1115. On average, the fields were about 1% high; however, the effective magnetic length was, on

average, about 3.5% longer than desired. As a consequence, the optimum energy for transmission through the achromat is 46 MeV rather than 45 MeV.

The measurements of the quadrupoles show (in Table 3-4) that the integration of their gradients over their length gives an effective $B' \times L_{\text{eff}}$ from 1.379 to 1.400 tesla. This compares with a design objective of 1.362 tesla. Thus, the achieved gradient $\times$ length products are about 2% high on average. This is in the same direction as the error in the dipoles. The achromat's trim coils will provide adequate compensation, since about 4% adjustment in effective gradient is available.

The vernier is designed to bend a 45 MeV electron beam 2° using two orthogonal sets of coils separately energized to control the direction and magnitude of the bend angle. Table 3-5 lists the target specifications and shows as-built values based on magnetic measurements. As can be seen, the required current is somewhat lower than targeted because the effective magnetic length is longer than initially projected. The coil resistance and the required voltage are slightly higher than the design objective.

A summary of the current, power, and voltage requirements for the achromat trim coils and the vernier is given in Table 3-6.

TABLE 3-1. ACHROMAT CHARACTERISTICS

ENERGY	45 MeV Electrons
LATTICE	(Q _F B Q _D Q _D B Q _F) x 4
MAGNET DEVICES	Permanent magnet dipoles Permanent magnet quadrupoles
BEAM TUBE APERTURE	2.84 cm
MAGNET APERTURE	3.24 cm

QUADRUPOLE CHARACTERISTICS (16 QUADS)

Gradient	0.1281 T/cm
Length	5.315 cm
R1	1.62 cm
R2	2.36 cm
Magnet weight	8.85 kg

DIPOLE CHARACTERISTICS (8 DIPOLES)

B	0.1104 T
Length	9.00 cm
R1	1.62 cm
R2	2.23 cm
Magnet weight	2.60 kg

PERMANENT MAGNET MATERIAL

Ferrimag	7B
B _r	0.3800 T
H _c	3500 Oe
w	4.8 g/cm ³
μ rev	1.05 - 1.07

TRIM COIL CHARACTERISTICS

Δ gradient	0.00256 T/cm (2%)
Current	10.8 amp
Voltage	105 volt
Power	1134 watt
Inductance	1.5 mH

COOLING

Water cooled	
Flow required	0.7 gpm

QUADRUPOLES AND BENDING MAGNETS (DIPOLES)

FIGURE 3-2. PERMANENT MAGNET DIPOLE

16 PERMANENT MAGNET SEGMENTS

Arrows show direction of magnetization

FIGURE 3-3. PERMANENT MAGNET QUADRUPOLE

16 PERMANENT MAGNET SEGMENTS

Arrows show direction of magnetization

TABLE 3-2. BEAM PATH THROUGH ACHROMAT WITH SHOWN ELEMENTS

LATTICE ITEM		LENGTH CM	--- A11	--- A12	MATRIX ELEMENTS A13 A21 A22	--- A23	DISTANCE CM	DELTA R CM	R-PRIME RAD	DEL P/P	NEET R	NEET R'	PHASE SPACE DEL R DEL R'	ANGLE DEGREES	R-DIST. INCHES	Y-DIST. INCHES	Z-MOM. DEGREES	Y-MOM. DEGREES	ANGLE DEGREES
LAC L= 3.31500 LAD S= 1401.30 BEND L= 9.00000 R/RAD= 166466.7 RHD = 137.51 0.09128 0.24617 RAD L= 119.10																			
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	0.0	-0.31760	0.02534	0.00000	-0.25907	0.01891	0.61939	0.00000	0.00000	1.046	0.00000	0.00000
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	2.7	-0.25907	0.01891	0.00000	-0.21611	0.01310	0.57215	0.00000	2.093	0.00000	2.09241	0.01824
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	5.3	-0.21611	0.01310	0.00000	-0.15480	0.01265	0.52415	0.00046	3.064	0.029	0.05796	0.04521
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	9.8	-0.15480	0.01265	0.00000	-0.09332	0.01368	0.47245	0.00126	5.834	0.116	5.63569	0.13465
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	14.3	-0.09332	0.01368	0.00000	-0.05457	0.01534	0.42090	0.01698	6.678	0.184	6.46782	0.16899
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	17.0	-0.05457	0.01368	0.00000	-0.01258	0.01610	0.36930	0.02111	7.722	0.253	7.71283	0.25279
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	19.6	-0.01258	0.01610	0.00000	0.03015	0.01590	0.31757	0.02534	8.766	0.321	8.76653	0.32535
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	22.3	0.03015	0.01590	0.00000	0.07118	0.01474	0.26595	0.02957	9.810	0.396	9.60523	0.40812
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	24.9	0.07118	0.01474	0.00000	0.13747	0.01474	0.21835	0.03177	11.576	0.534	0.56325	11.57391
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	28.4	0.13747	0.01474	0.00000	0.20349	0.01469	0.16275	0.03062	13.356	0.737	13.33567	0.75537
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	33.9	0.20349	0.01469	0.00000	0.24924	0.01775	0.11113	0.04224	14.373	0.873	14.37308	0.87812
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	36.6	0.24924	0.01775	0.00000	0.30971	0.02599	0.05434	0.04646	15.611	1.018	15.61248	1.01607
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	39.3	0.30971	0.02599	0.00000	0.38075	0.03379	0.00000	0.05069	16.448	1.147	16.44929	1.15121
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	41.9	0.38075	0.03379	0.00000	0.47187	0.04361	0.04452	0.04452	17.485	1.283	17.48648	1.30153
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	44.6	0.47187	0.04361	0.00000	0.56780	0.05457	0.11165	0.04224	19.378	1.543	19.37819	1.57617
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	49.1	0.56780	0.05457	0.00000	0.68219	0.04328	0.16313	0.03802	20.901	1.866	20.90056	1.87863
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	53.6	0.68219	0.04328	0.00000	0.84990	0.02244	0.21462	0.03379	22.007	2.044	22.00934	2.04504
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	56.2	0.84990	0.02244	0.00000	1.00607	0.00919	0.24613	0.02957	23.033	2.248	23.03639	2.24846
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	58.9	1.00607	0.00919	0.00000	0.97091	-0.02203	-0.31760	0.02534	24.059	2.473	24.06163	2.47724
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	61.5	0.97091	-0.02203	0.00000	0.80415	-0.04294	-0.36920	0.02111	25.004	2.677	25.00499	2.67995
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	64.2	0.80415	-0.04294	0.00000	0.67048	-0.04315	-0.26050	0.01690	25.983	3.051	26.01332	3.06121
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	68.7	0.67048	-0.04315	0.00000	0.49664	-0.04327	-0.07200	0.01267	26.933	3.481	26.93362	3.49423
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	73.2	0.49664	-0.04327	0.00000	0.39479	-0.03333	-0.32356	0.00844	27.944	3.752	27.94975	3.75622
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	78.5	0.39479	-0.03333	0.00000	0.31717	-0.02538	-0.57150	0.00422	28.953	4.023	28.95155	4.02300
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	83.8	0.31717	-0.02538	0.00000	0.25856	-0.01895	-0.81890	0.00000	29.964	4.294	31.37094	4.29824
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	81.2	0.25856	-0.01895	0.00000	0.21517	-0.01366	-0.61860	0.00000	32.578	4.544	32.57789	4.58240
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	83.8	0.21517	-0.01366	0.00000	0.15365	-0.01371	-0.57150	0.00422	34.281	5.351	34.27700	5.36589
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	88.3	0.15365	-0.01371	0.00000	0.09218	-0.01374	-0.52356	0.00844	35.768	5.935	35.76653	5.91081
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	92.8	0.09218	-0.01374	0.00000	0.06325	-0.01357	-0.47200	0.01267	36.959	5.979	36.96166	5.93588
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	95.3	0.06325	-0.01357	0.00000	0.01120	-0.01610	-0.42050	0.01690	37.848	6.745	37.85566	6.72575
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	99.2	0.01120	-0.01610	0.00000	-0.03169	-0.01587	-0.36920	0.02111	38.940	7.599	38.94313	7.59211
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	100.8	-0.03169	-0.01587	0.00000	-0.07332	-0.01474	-0.31760	0.02534	39.951	8.402	39.95132	8.40581
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	103.5	-0.07332	-0.01474	0.00000	-0.11842	-0.01468	-0.26613	0.02957	40.959	9.255	40.95964	9.26724
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	108.0	-0.11842	-0.01468	0.00000	-0.13948	-0.01464	-0.21462	0.03379	41.966	1.064	41.96745	1.07075
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	112.5	-0.20349	0.01469	0.00000	-0.24978	0.01970	-0.16313	0.03602	42.973	1.826	42.97302	1.82954
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	115.1	-0.24978	0.01970	0.00000	-0.31615	0.02599	-0.11183	0.04224	43.980	2.587	43.97792	2.59276
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	117.0	-0.31615	0.02599	0.00000	-0.38910	0.03379	-0.05434	0.04646	44.985	3.297	44.98272	3.29787
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	120.4	-0.38910	0.03379	0.00000	-0.49337	0.04359	0.00000	0.05069	45.992	4.077	45.99280	4.08048
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	123.1	-0.49337	0.04359	0.00000	-0.60719	0.05457	0.11165	0.04224	46.998	4.852	46.99856	4.86012
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	127.6	-0.60719	0.05457	0.00000	-0.74997	0.06717	0.16313	0.03802	47.998	5.627	47.99819	5.63015
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	132.1	-0.74997	0.06717	0.00000	-0.91997	0.08219	0.21462	0.03379	48.998	6.402	48.99819	6.40581
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	136.8	-0.91997	0.08219	0.00000	-1.06007	0.10000	0.16313	0.03802	49.998	7.177	49.99819	7.18048
QF	2.658	0.97034	2.63117	0.00000	-0.02721	0.97034	0.00000	137.4	-1.06007	0.10000	0.00000	-1.20000	0.12000	0.16313	0.03802	50.998	7.952	50.99819	7.95481
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	140.1	-1.20000	0.12000	0.00000	-1.34000	0.14000	0.16313	0.03802	51.998	8.727	51.99819	8.73048
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	142.7	-1.34000	0.14000	0.00000	-1.48000	0.16000	0.16313	0.03802	52.998	9.502	52.99819	9.50481
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	147.2	-1.48000	0.16000	0.00000	-1.62000	0.18000	0.16313	0.03802	53.998	10.277	53.99819	10.28048
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	151.7	-1.62000	0.18000	0.00000	-1.76000	0.20000	0.16313	0.03802	54.998	11.052	54.99819	11.05481
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	154.4	-1.76000	0.20000	0.00000	-1.90000	0.22000	0.16313	0.03802	55.998	11.827	55.99819	11.83048
QD	2.658	1.02996	2.68399	0.00000	0.02766	1.02996	0.00000	157.0	-1.90000	0.22000	0.00000	-2.04000	0.24000	0.16313	0.03802	56.998	12.602	56.99819	12.60481

TABLE 3-3. PERMANENT MAGNET DIPOLES
22 November 1985

<u>S/N</u>	<u>B x L_{eff}</u> <u>(T/m)</u>	<u>B</u> <u>(T)</u>	<u>Dipole Dev.</u> <u>(degree)</u>	<u>Quadrupole</u> <u>Relative</u> <u>%</u>	<u>Sextupole</u> <u>Relative</u> <u>%</u>
B1	0.01030	0.1120	-0.43	0.5	4.8
B2	0.01027	0.1117	-1.14	2.0	4.5
B3	0.01028	0.1117	+1.00	2.7	4.0
B4	0.01028	0.1115	+0.01	2.2	6.0
B5	0.01032	0.1119	-0.74	1.2	5.0
B6	0.01033	0.1124	-0.93	1.0	4.1
B7	0.01034	0.1123	-0.32	2.4	4.5
B8	0.01030	0.1117	-0.46	0.6	3.4
B9	0.01035	0.1126	-1.01	1.0	2.7
B1*	0.01029	0.1119	-0.96	0.5	4.8

*Measurement redone.

TABLE 3-4. QUADRUPOLE ASSEMBLIES MEASUREMENTS SUMMARIZATION

DATASET	QUAD ID	ORIENT	SC AXIS OFFSET (mm)	SC AXIS ANGLE (deg)	B'Leff (Tesla)	QUAD ANGLE (deg)	ALPHA D (deg)	BLeff (mT-K)
1106C0	8D	Norm	0.16	98.3	1.379	4.4	0.125	0.221
1106C1	8D	Norm	0.16	97.9	1.379	4.4		
1106C2	8D	Rev	0.17	-111.9	1.379	-175.1		
1106C3	8D	Rev	0.17	-111.9	1.380	-175.1		
1125A0	1F	Norm	0.06	27.2	1.387	5.5	0.100	0.083
1125A1	1F	Norm	0.06	28.0	1.386	5.5		0.083
1125A2	1F	Rev	0.04	-147.6	1.388	-174.9		0.056
1125A3	1F	Rev	0.04	-148.0	1.388	-175.0		0.056
1106C8	2D	Rev	0.09	-106.5	1.374	-176.0	-0.375	0.124
1106C9	2D	Rev	0.09	-107.0	1.375	-176.0		
1106D0	2D	Norm	0.10	67.7	1.376	5.5		
1106B1	2D	Norm	0.10	66.4	1.377	5.4		
1106D2	3F	Norm	0.05	70.2	1.381	5.3	-0.250	0.069
1106B3	3F	Rev	0.06	-174.7	1.386	-175.7		
1108B0	4F	Norm	0.20	43.2	1.388	5.7	-0.150	0.278
1108B1	4F	Norm	0.19	42.8	1.388	5.6		0.264
1108B2	4F	Rev	0.18	-35.1	1.389	-174.9		0.250
1108B3	4F	Rev	0.18	-35.0	1.390	-174.9		0.250
1108D0	5F	Norm	0.01	163.8	1.398	5.7	-0.525	0.014
1108D1	5F	Norm	0.01	168.0	1.397	5.7		0.014
1108D2	5F	Rev	0.04	-178.8	1.399	-176.4		0.056
1108D3	5F	Rev	0.03	174.8	1.398	-176.4		0.042
1125C0	6D	Norm	0.07	21.9	1.400	5.0	0.200	0.098
1125C1	6D	Norm	0.07	22.0	1.400	5.0		0.098
1125C2	6D	Rev	0.04	-141.3	1.402	-174.2		0.056
1125C3	6D	Rev	0.04	-141.4	1.402	-174.2		0.056
1125B0	7D	Norm	0.11	85.5	1.400	4.8	0.413	0.154
1125B1	7D	Norm	0.10	85.8	1.400	4.8		0.140
1125B2	7D	Rev	0.13	-123.0	1.400	-173.0		0.182
1125B3	7D	Rev	0.13	-123.8	1.401	-174.4		0.182
1125D0	8D	Norm	0.15	80.0	1.383	5.1	0.100	0.207
1125D1	8D	Norm	0.15	79.7	1.383	5.1		0.207
1125D2	8D	Rev	0.16	-115.6	1.384	-174.5		0.221
1125D3	8D	Rev	0.16	-115.2	1.383	-174.5		0.221
1106E4	S1	Norm	0.16	-64.4	0.696	4.6	0.300	0.111
1106E5	S1	Rev	0.10	98.1	0.696	-174.2		
1106E6	S2	Norm	0.09	164.9	0.694	5.7	-0.025	0.062
1106E7	S2	Rev	0.14	-173.9	0.694	-174.4		

TABLE 3-5. VERNIER CHARACTERISTICS

COIL LENGTH	40 cm	
MAXIMUM FIELD	147 gauss $\pm$ 0.5%	
MAXIMUM BEND	$\pm$ 2° $\pm$ 0.5%	
DIRECTION	X or Y	
<u>PROJECTED VALUE</u>	<u>X - COILS</u>	<u>Y - COILS</u>
COIL RADIUS - inches	1.5	1.25
NUMBER OF COIL TURNS	78	78
COIL RESISTANCE - ohms	0.766	0.736
CURRENT FOR 2° BEND - amps	22.8	19.0
VOLTAGE - volts	17.5	14.0
INDUCTANCE - mH	1.26	1.05
MATERIAL	ALUM	ALUM
WEIGHT - pounds	1.6	1.5
<u>AS BUILT VALUES FOR 45 MeV</u>		
CURRENT FOR 2° BEND - amps	18.3	15.25
COIL RESISTANCE - ohms	1.00	0.95
VOLTAGE - volts	18.3	14.5
EFFECTIVE MAGNETIC LENGTH - cm	46	45

TABLE 3-6. POWER SUPPLIES AND EXPECTED FIELDS FOR
BEAM DIRECTOR COMPONENTS

ACHROMAT TRIM COILS

Conductors: 18 ga., 56 turns/slot
 Conductor length = 2400 feet
 Conductor resistance = 15.0 ohms total
 Connections: all coils in series
 Current @ 25.3 G/cm = 4.35 amps
 Maximum current total = 4.5 amps
 Maximum DC voltage = 67.5 volts
 Inductance = 6.0 mH
 Time constant = 0.40 ms

Power Supply

Maximum current = 6 amps
 Maximum voltage = 100 volts
 Regulation = 0.1%
 Preferred current regulation: pulse basis

VERNIER STEERING MAGNET

X-Coils

Conductor length = 262 feet
 Conductor resistance = 0.256 ohms
 Current @ 132 G = 20.83 amps
 Voltage @ 20.83A = 5.33 volts

Y-Coils

Conductor length = 252 feet
 Conductor resistance = 0.246 ohms
 Current @ 132 G = 17.14 amps
 Voltage @ 17.14A = 4.22 volts

Power Supply

Two power supplies needed
 Maximum current = 25 amps
 Maximum voltage = 8 volts
 Regulation = 0.01%
 Preferred current regulation: pulse basis

4.0 PHOTOGRAPHS

4-1. PERMANENT MAGNET ASSEMBLY

The achromat contains 17 of these assemblies, each consisting of 16 trapezoidal-wedge magnet segments, installed in an aluminum segment carrier. This particular assembly can be identified as a quadrupole by the pattern of the arrows on the ends of the wedges.

4-2. PARTIALLY ASSEMBLED ACHROMAT

This picture shows all 17 permanent magnet assemblies, with one of them removed from its position. The achromat consists of 8 dipoles and 9 quadrupoles, 5 of which are defocusing quads, and 4 of which are focusing. The two defocusing quads on the ends, as can be seen, are short. The sequence is:

dQ D fQ D dQ D fQ D dQ D (removed) fQ D dQ D fQ D dQ

The magnets have been placed into one half of the achromat housing for this picture. When the achromat was actually assembled, the magnets were installed on the beam tube before being placed in the housing.

4-3. ASSEMBLED ACHROMAT

In the completed achromat, the housing encloses the magnet assemblies, which surround the beam tube. The beam tube can be seen protruding at each end of the achromat.

4-4. VERNIER COIL MATERIAL READY TO ANODIZE

Aluminum strip for the vernier coils being wound onto a reel in preparation for anodizing. 1,200 feet of strip was prepared for use in the X coils and Y coils of the vernier. Although the anodizing probably would have sufficiently insulated the individual layers of coil material, as an extra measure of safety, one side of the strip was covered with mylar film tape before the coils were built.

4-5(a)

4-5(b)

4-5(c)

4-5. ASSEMBLED VERNIER

The direction of the beam in the side view (c) is from right to left. The two end views show the downstream end (a) and the upstream end (b). One set of concentric X coils is clearly shown in the side view. The somewhat smaller Y coils are inside them, rotated 90°, so that their edges are barely visible in the side view. The edges of both sets of X coils and both sets of Y coils are visible in the downstream end view.

The bent tubing surrounding the vernier is the cooling coils.

4-6. VERNIER MEASUREMENT SET-UP

Magnetic measurements of the vernier were made at Lawrence Berkeley Laboratory using this set-up.

4.7 VERNIER ASSEMBLY TEST MOUNT

The vernier was installed in this experimental tank for testing in the Brobeck Corporation shop. In addition to vacuum leak testing, the vernier coils were operated briefly at design current in vacuum.

4.8 ACHROMAT AND VERNIER ASSEMBLIES READY TO SHIP

4-9. ACHROMAT INSTALLED FOR BEAM TEST

This picture shows the achromat installed at Lawrence Livermore National Laboratory for low level beam current testing at 45 MeV. The direction of the beam is from left to right; the target is out of sight on the far right.

A test at full power is planned for a later date, to be determined by the ATA operating schedule.

5.0 ANALYSIS AND COMPUTATION

5.1 ACHROMAT

The analysis and design calculations for the achromat can be divided into two categories--one for the beam steering and focusing, and the other for the magnetic fields of the various components.

5.1.a Steering and Focusing

The analysis and design calculations for beam steering and focusing were done by the matrix transformation method used in the TRANSPORT computer program (see §11.0, References). This matrix method is used to compute the trajectories of particles in terms of their deviations from the central path of the on-energy, on-axis particle. For first-order optics, the change in the phase-space coordinates of charged particles passing through a magnetic lens or steering element is found from the linear magnetic properties of the magnetic element represented by a square matrix. The transformed phase-space coordinates are found by the following matrix multiplication:

$$X = R X_i$$

where

$$\begin{aligned} X_i &= \text{initial coordinates} \\ X_o &= \text{final coordinates} \\ R &= 6 \times 6 \text{ transformation matrix} \end{aligned}$$

The phase-space coordinate, X , is a vector (single column matrix) whose components are the positions, slopes, and momentum of the particle with respect to the particle on the central path or referenced trajectory, such that

$$X = \begin{bmatrix} x \\ \theta \\ y \\ \phi \\ z \\ s \end{bmatrix}$$

Definitions:

- x = the horizontal displacement of the arbitrary ray with respect to the assumed central trajectory.
- θ = the angle this ray makes in the horizontal plane with respect to the assumed central trajectory.
- y = the vertical displacement of the ray with respect to the assumed central trajectory.
- ϕ = the vertical angle of the ray with respect to the assumed central trajectory.
- z = the path length difference between the arbitrary ray and the central trajectory.
- s = $\Delta p/p$ = the fractional momentum deviation of the ray from the assumed central trajectory.

The transformation matrix, R, describes the action of the magnet on the particle's coordinates as the charged particle passes through the magnetic element. The transformation matrices encountered in the achromat are those for wedge-type bending magnets and for quadrupoles.

The first-order matrix for the wedge bending magnet is given in Figure 5-1. For our achromat, the field index, n, is zero, so the matrix elements a_{33} and a_{44} are equal to unity, the matrix element a_{34} equals L, and a_{43} equals zero.

The radius of curvature, ρ_0 , is found from the magnetic field, B, of the bending magnet and the magnetic rigidity ($B\rho$), of the high energy electron. This radius of curvature, the magnet length, and the spacing between the magnets are used for constructing a geometric layout of the central path trajectory.

The magnetic rigidity of an electron is found from

$$B\rho = \frac{(T(T + 2W_0))^{1/2}}{299.79} \text{ T}\cdot\text{m}$$

Where

B = magnetic field, in tesla

P = bend radius, in meters

T = electron energy, in MeV

W_0 = electron rest mass, in MeV

The denominator is the speed of light divided by 10^6 to make the units consistent.

For 45 MeV electrons ($W_0 = 0.51098$) the magnetic rigidity is found to be:

$$B\rho = 0.1518 \text{ T}\cdot\text{m}$$

For the achromat, eight bending magnets, each 9 cm long, give a total bend of 30° ($\pi/6$ radians). Thus, the required magnetic field is found as follows:

$$B = \frac{a(B\rho)}{L}$$

$$B = \frac{\pi/6 \times 0.1518}{8 \times 0.09} = 0.1104 \text{ tesla}$$

The radius of curvature, ρ_0 , is found as follows:

$$\rho_0 = \frac{0.1518}{0.1104} = 1.375 \text{ meters}$$

The elements in the wedge magnet transformation matrix are functions of this radius of curvature and of the magnetic length.

The first-order matrix for the quadrupoles is given in Figure 5-2. The value B_0/a is conventionally referred to as the quadrupole's gradient.

An examination of the non-zero elements in the sixth column of the bending magnet's transformation matrix shows that the coordinates x , θ , and y are affected by the fractional momentum deviation, $\Delta p/p$. This sensitivity to a momentum deviation causes a chromatic aberration. Compensating for this aberration is one of the main functions of the quadrupoles in the achromat. The quadrupoles also act to limit the beam's transverse dimensions.

A first-order correction for chromatic aberration can be achieved by a symmetrical arrangement of a number of identical groups (or cells) of quadrupoles and bending magnets. One such grouping is shown in Figure 5-3. This grouping may be referred to as a FODOF cell because it has a focusing quadrupole at each end and two defocusing quadrupoles in the center. To provide achromaticity, at least four cells are required with a phase advance per cell of $\pi/2$. A four-cell arrangement would then give a 2π phase advance for particles passing through the achromat. (As noted earlier, the final design used defocusing rather than focusing quads at the ends, so the unit cells were actually DOFFO cells).

It has been shown that this arrangement of cells can be converted to a second-order achromat also having second-order corrections for geometric aberrations by the addition of eight sextupoles. This should be considered as a possibility for future improvements in the achromat.

A spreadsheet program was set up for calculating the matrix elements and performing the matrix multiplications for computing the trajectories of particles passing through the achromat. This program, using Lotus 1-2-3 software, was arranged to give a graphical display of the trajectories. Values of key parameters, such as the quadrupole gradient and length of various elements, are easily changed with the resulting changes in trajectories quickly computed and graphically displayed. Rapid iterations are possible, so the desired quadrupole characteristics needed to achieve achromaticity are readily found.

Tables 5-1, 5-2, and 5-3 show the results of the spreadsheet calculations and Figures 5-4, 5-5, and 5-6 show the corresponding trajectories. It can be seen that the 2π phase advance for the horizontal phase-space coordinates x and θ was achieved and that this resulted in an achromatic bending system. The vertical phase-space coordinates y and ϕ do not have an exact 2π phase

advance, but this does not indicate any loss in achromaticity.

A 1% change in quadrupole gradient makes a small but noticeable change in the horizontal offset of the off-energy beam as seen in Table 5-4 and Figure 5-7 which should be compared with those previously shown in Table 5-3 and Figure 5-6. Because the achromaticity is fairly sensitive to the quadrupole gradient, a means of adjusting and controlling this gradient is required.

These steering and focusing calculations give the desired achromat characteristics shown in Table 5-5.

5.1.b Magnetic Field Calculations

The dipole and quadrupole fields required for the achromat are generated by sixteen trapezoidal permanent magnet wedges supported around the beam tube as shown in Figures 5-8 and 5-9. The direction of magnetization of each of the trapezoidal pieces shown in the figures produces the type of field desired. The magnetic fields are calculated from equations developed by Klaus Halbach for designing rare-earth-cobalt quadrupoles. These equations can be applied to other types of permanent magnet materials if the material has a nearly linear demagnetization curve and a permeability of unity. These restrictions apply because the derivation of the equations is based upon linear superposition.

For our achromat, a grain-oriented ferrite permanent magnet material with a linear demagnetization curve and a permeability very close to unity was selected ($\mu_0 = 1.05$ to 1.07). Because the permeability is not precisely unity, the magnetic devices are expected to have some higher-order harmonics coming from terms ignored in the calculations.

From linear superposition, the resultant dipole field is given as follows:

$$B = B_r \cos \left(\frac{\pi}{M} \right) \times \ln \left(\frac{r_2}{r_1} \right)$$

where B = the dipole field
 B_r = residual induction
 M = number of segments
 r_2 = outer radius of segments
 r_1 = inner radius of segments

For a quadrupole, the equation for the field at the inner radius is as follows:

$$B(r_1) = 2 B_r \cos^2 (\pi/M) \times \frac{\sin (2\pi/M)}{2\pi/M} \times \left(1 - \frac{r_1}{r_2}\right)$$

where $B(r_1)$ = maximum field at r_1
 B_r = residual induction
 M = number of trapezoidal segments
 r_2 = outer radius of segments
 r_1 = inner radius of segments

For $M = 16$, these equations reduce to the following:

$$\text{Dipole, } B = 0.981 B_r \times \ln (r_2/r_1)$$

$$\text{Quadrupole, } B(r_1) = 1.875 B_r \times \left(1 - \frac{r_1}{r_2}\right)$$

The measured value B_r for the permanent magnet material (Ferrimag 7B) is 0.357 T. Using this value and the design values for the inner and outer radius for the dipole segments

$$r_1 = 1.62 \text{ cm}$$

$$r_2 = 2.23 \text{ cm}$$

the calculated dipole field is found as

$$B = 0.981 \times 0.357 \times \ln (2.23/1.62)$$

$$B = 0.1119 \text{ T} \quad (\text{design})$$

This compares with the desired value of

$$B = 0.1104 \text{ T} \quad (\text{desired})$$

and measured value of the finished dipole

$$B = 0.1120 \text{ T} \quad (\text{average measured value in center})$$

$$\text{Effective } B = 0.1145 \text{ T} \quad (\text{average effective value})$$

For the quadrupole, the fields are calculated using the design values for the inner and outer radius for the quadrupole segments

$$r_1 = 1.62 \text{ cm}$$

$$r_2 = 2.36 \text{ cm}$$

The calculated quadrupole field at the inner radius is found as

$$B(r_1) = 1.875 \times 0.357 \times \left(1 - \frac{1.62}{2.36} \right)$$

$$B(r_1) = 0.2099 \text{ T}$$

For which the gradient, G , is found as

$$G = \frac{0.2099}{0.0162} = 12.96 \text{ T/m} \quad (\text{design})$$

This compares with the desired value of

$$G = 12.81 \text{ T/m} \quad (\text{desired})$$

and the measured effective value

$$G = 13.07 \text{ T/m} \quad (\text{measured average})$$

Thus, the measured gradient is 2% higher than the ideal value calculated for the achromat and the measured bending magnet effective field is 3.7% high.

Using these measured values, the corrected design point energy of the achromat is found by iteration to be 46.7 MeV.

The required quadrupole gradient, G_n , is then found from the change in magnetic rigidity:

$$G_n = 12.81 \times \frac{(46.7 (46.7 + 2 \times 0.511))^{1/2}}{(45 (45 + 2 \times 0.511))^{1/2}}$$

$$G_n = 13.29 \text{ T/m}$$

which compares with the measured value of 13.07 T/m.

The trim coils, which are designed to give a $\pm 4\%$ adjustment in quadrupole gradient, will be required to give only a 1% increase in gradient.

5.1.c Sorting of Magnetic Segments

For design purposes, the trapezoidal magnetic segments that fit together to produce the dipole and quadrupole fields were assumed to have ideal physical and magnetic geometries as well as consistent magnetic properties. In reality, slight variations in geometric and magnetic properties should be expected. Since these variations could create unacceptable errors in field shape (harmonics) and in field magnitude, a means for minimizing the adverse affects of normal variations is needed. The concept study conducted in 1983 (Appendix G, Volume II) indicated a desirability to limit the field error to less than 2%.

To achieve the desired objective, all magnetic material used in the design was from the same batch and all trapezoidal segments were measured by the Magnetic Measurements Engineering Group at Lawrence Berkeley Laboratory (LBL) to determine their magnetic moment vectors. Segments with excessive deviations in their magnetic vectors were rejected. (Allowance for rejects was made in advance by ordering extra segments.) Acceptable segments were sorted to minimize accumulative errors.

The sorting process was quite simple. The magnetic measurements received from LBL had been presorted by magnet type (dipole or quadrupole) and by angular orientation of the magnetic vector corresponding to a particular position in the finished magnetic device. A sample of this data is shown in Table 5-6. As may be seen, the data are arranged in order of increasing magnetic moment (MX_Y) and clearly show the measured angle. The high and low values of moment as well as the distribution are clearly shown. By subtracting the reference

angle (180°) from the measured angle (THTAXY), the angular error is easily found. Segments with large angular errors were preferentially rejected. From the table, it can be seen that magnet segment #301153 has an angular error of 6.4° and would probably be rejected. Most of the angular errors are less than 2° .

Where all the angular errors are small (usually the case), segments with the largest deviations in magnetic moments would be rejected. Of the segments shown in the table, #301185 is the only segment that might have too high a moment. A preliminary sorting is done simply by scanning the measurement data.

The next step of sorting is done by a vector summation of magnetic moments for segments assigned to specific locations in an assembled device. Figure 5-10 shows an end view of a quadrupole with the sixteen segments in labeled positions #1 through #16. A magnetic segment such as #301217 (or any 301xxx) can be used in either of the two positions, #1 or #9. Similarly, any segment with a 302xxx designation can be used in the positions labeled #2 or #10. In the coordinate system of the quadrupole, the direction of the magnetic vector of an installed segment (the global angle) is found from its local vector angle to its positional angle. The figure shows the ideal global angles; for example, at position #3, the ideal global angle is -135° . A segment for this location would have a design angle of 90° . If its measured angle were 92° (an error of $+2$), its global angle would be -133 ($-135 + 2 = -133$).

The horizontal vertical components of the magnetic vector at any location is found from

$$M_h = M \cos \theta$$

$$M_v = M \sin \theta$$

Where M = magnetic moment, MXV

θ = global angle

Theoretically, the summation of the vectors for all locations should equal zero. Because there are angular errors and variations in moments, the summations will not be exactly zero. A small value may indicate that the overall errors are small. A sorting technique designed to minimize the vector sums is used.

A spreadsheet program was set up for computing the vector sums due to magnet segments assigned to different positions. A block of 32 segments of suitable type and orientation to make two quadrupoles or two dipoles were selected from the preliminary sorting operation. Their magnetic properties and identification codes were entered into the program. Their positions could then be juggled in a systematic way to bring the magnetic vector sum to less than 1/2% of the sum of the absolute moments.

The results of the calculations for the quadrupoles and for the dipoles are shown in Tables 5 through 14 in the Final Report (included as Appendix H, Volume II). Each of these tables was generated by manually juggling the positions of the segments. The segment identification numbers were then transferred to a working sketch such as the one shown in Figure 5-11. This sketch was used in the shop for the magnet assembly.

5.1.d Trim Coils for Achromat

Trim coils are provided on the achromat for adjusting the quadrupole gradients. These are located in grooves on the outside of the achromat housing which places the center of the conductor bundle at a radius of 1.49

inches. Each conductor bundle is about 10.3° away from the horizontal and vertical axes. Each coil bundle contains 56 turns of #18 copper wire. For computation of the magnetic fields due to these trim coils, the program developed for the vernier (pp. 5-15, 5-16) is used. For calculational purposes, the 56 turns are divided into two groups of 28 turns each placed at angles of 7.34° and 13.24° away from the horizontal and vertical axes. The computations in spreadsheet format are shown in Table 5-7. At the current of 8.8 amperes shown, the field at a radius of one centimeter (0.3937") is 51.278 gauss which corresponds to a gradient of 0.51 T/m. This is approximately 4% of the quadrupole design value of 12.81 T/m.

The measured values of magnetic fields for the dipoles and quadrupoles indicate that the actual requirement may be much less than 4%. It appears that a 2% correction is more than adequate so a maximum trim coil current of 4.5 amperes should be adequate.

The trim coil resistance and power requirement is calculated using a resistance of #18 wire of $6.5\ \Omega$ per 1,000 ft at 25°C . The total coil length is calculated to be 2,400 ft which gives a resistance

$$R = 2.4 \times 6.5 = 15.6\ \Omega$$

(measured value is $15\ \Omega$)

At 4.5 amperes, the power and voltage drop is found as

$$V = 4.5 \times 15.6 = 70.2\ \text{volts}$$

$$P = 4.5^2 \times 15.6 = 316\ \text{watts}$$

Convective heat transfer from the coils is calculated on the basis of a free convection heat transfer coefficient of $4\ \text{Btu/hr ft}^2\ ^\circ\text{F}$ and transient heating is calculated on the basis of no heat transfer.

The convective heat transfer is found from

$$Q = h A \Delta t$$

Each full coil has an area of 20.9 in² and there are 28 full coils and 8 short quad coils. Using 32 coils as a suitable number, the total area is found as follows:

$$A = 20.9 \times 32/144 = 4.64 \text{ ft}^2$$

The heat input in Btu is found as

$$Q = 316 \text{ watts} \times 3.412 \frac{\text{Btu}}{\text{watt hr}} = 1,078 \text{ Btu/hr}$$

The temperature rise at the coil surface is then found

$$\Delta T = \frac{Q}{hA} = \frac{1078}{4 \times 4.64} = 58^\circ\text{F}$$

This does not appear to be excessive; however, it has not been shown that a free convection heat transfer coefficient of 4 Btu/hr ft² °F will be achieved.

In the absence of significant heat transfer (say at low pressure), a transient temperature rise will occur where the time for a given temperature rise is found from

$$\Delta t = \frac{C_p W \Delta T}{Q}$$

where the coil weight W is 2.4 x 4.92 = 11.81 lbs

the specific heat $C_p = \frac{175 \text{ watt seconds}}{\text{# } ^\circ\text{C}}$

Thus, for a temperature rise of $\Delta T = 40^\circ\text{C}$, the time for Δt is

$$\Delta t = \frac{175 \times 11.81 \times 40}{316} = 261 \text{ seconds} = 4.36 \text{ minutes}$$

Therefore, it appears reasonable to operate in an intermittent mode if the heat transfer environment is poor.

5.2 VERNIER

For the analysis of the vernier steering magnet, it is convenient to consider the unit oriented in an orthogonal coordinate system with a vertical y axis and horizontal x and z axes. The unit is set in this coordinate system with the undeflected beam path aligned with the z axis. A set of coils to produce magnetic flux lines parallel to the y axis with a magnetic strength B_y will cause the electron beam to bend in the horizontal plane. An additional set of coils rotated 90° with respect to the first set will produce magnetic flux lines parallel to the x axis with a strength B_x which will cause an electron beam to bend vertically out of the horizontal plane. Energizing both sets of coils produces the magnetic vector at a non-orthogonal angle to the horizontal plane and will give a bend with both horizontal and vertical components.

At a given energy, the bend angle is proportional to the magnetic field strength. Control of the field strength gives control of the bend angle. The bend angle in radians is found by dividing the product of the magnetic field (B) and the effective length (L) by the magnetic rigidity of the electron beam

$$\alpha = \frac{B \times L}{(B\rho)} \quad (\text{in radians})$$

where B = magnetic field vector, in tesla

L = effective length of vernier, in meters

$(B\rho)$ = magnetic rigidity, in T·m (tesla meters)

The magnetic rigidity for 45 MeV electrons was calculated in the achromat analysis (§5.1.a) where the value of 0.1518 T·m is found.

For an effective length of 40 cm and a bend of 2° ($\pi/90$ radians), the required magnetic field is found as follows:

$$B = \frac{\alpha(B_D)}{L}$$

$$B = \frac{\pi/90 \times 0.1518}{0.4} = 0.01325 \text{ T} = 132.5 \text{ gauss}$$

This value is small enough to allow the use of a lightweight ironless design. The absence of iron in the flux path simplifies the magnetic field calculations.

The magnetic field in the central region of the vernier is found by vectorially adding the field contributions from each of the conductors in the coil. The field contributions from each conductor is a vector of magnitude given as follows:

$$B = \frac{\mu \cdot I}{2\pi r}$$

where B = magnetic field, in T

I = current, in A

r = radius, in m

$$\mu_0 = 4\pi \times 10^{-7} \text{ Wb/A}\cdot\text{m}$$

The B vector is perpendicular to the radius vector in a direction determined by the righthand rule.

To find B in gauss with the radius in inches the equation reduces to:

$$B = \frac{I}{0.202 \times 2\pi r} \quad \text{gauss}$$

I in amperes

r in inches

An array of conductors is shown in Figure 5-12 to illustrate the method for calculating the field. In this figure, the center of the vernier is

located at point "o" as viewed looking down the vernier in the direction of the beam path. Conductors A, B, C, D, and E are located at a radial distance R from the center of the vernier. It is desired to calculate the field at any point, P, in the central region. The field contribution from a single conductor (B_c) is shown in the figure.

The coordinates of point P are given as x_1 and y_1 . The coordinates of conductor, B_c , are found from its angular position θ and radius R as

$$x_c = R \cos \theta$$

$$y_c = R \sin \theta$$

The radius vector from the conductor to the point is found as

$$r = \sqrt{(x_c - x_1)^2 + (y_c - y_1)^2}$$

The field vector at the point is found as

$$B = \frac{I}{0.202 \times 2\pi r}$$

The vector components B_x and B_y are found as

$$B_x = -B(y_c - y_1)/r$$

$$B_y = B(x_c - x_1)/r$$

Adding the vector contributions from all the conductors gives the resultant field at point P. To ensure that the magnetic field in the central region of the vernier is sufficiently uniform requires examining the field at a multitude of points within this region.

An extremely uniform dipole field in the interior region may be obtained by using a large number of closely spaced conductors with a cosine variation in current. A reasonable approximation for this cosine variation may be achieved with a limited number of conductors judiciously spaced around the circle if the ampere-turns assigned to each conductor position are properly proportioned.

The design approach for the vernier steering magnet was to select five angular positions in each quadrant arbitrarily, and then to calculate an appropriate number of coil turns to use at each of these positions. The turns assigned to each location are made proportional to the integral of the cosine evaluated over a range of angular values assigned to each coil.

For example, coil "C" is located at 45° and is assigned to cover the angular range from 37.5° to 52.5° . Its proportion of the total number of turns, q_c , is found by integration as follows:

$$q_c = \int_{37.5^\circ}^{52.5^\circ} \sin \psi d\psi = 0.1846$$

The integration is made for each coil location and integer values of turns are then assigned. Table 5-8 shows the values for the design as it evolved to its final configuration after a number of iterations.

A spreadsheet program for the calculation of the field contributions and resulting field vectors was set up. The results of these calculations are shown in Tables 5-9, 5-10, 5-11, 5-12, and 5-13. A plot of relative field values at a one-centimeter radius is shown in Figure 5-13. The variation in magnetic field is less than 0.1%. Most of this variation is due to the sextupole content.

The fringing fields at the ends of the vernier were not calculated. The ends of the coils curve up away from the beam path which should cause a fairly rapid drop off in the field. In spite of this, the fringe fields should make the effective length slightly longer than 40 cm.

Ohmic heating and electrical resistance calculations were based upon the following properties of the coils:

Material	Aluminum
Specific weight	0.10 lbs/in ³
Resistivity	1.2 micro-ohms-in
Cross section (actual)	0.020" x 0.250"
(effective)	0.018" x 0.250"
Specific heat	430 w-sec/# °C

The total length of the conductor and in the inner and outer coils were as follows:

Inner L = 3025 inches

Outer L = 3150 inches

The resistance of a coil is found from the following equation

$$R = \rho L/A, \text{ in ohms}$$

where ρ = resistivity, in ohm-in

L = length, in inches

A = cross sectional area, in in²

Using this equation, the following resistances were calculated

Inner coil, R = 0.83 ohms

Outer coil, R = 0.87 ohms

At the maximum magnetic field values, the following values for current, voltage, and power were calculated:

	<u>Inner Coil</u>	<u>Outer Coil</u>
current, A	17.2	20.83
voltage, V	14.0	17.3
power, W	240	360

Since the coils may be operating in a vacuum, it will be difficult to dissipate the power on a continuous basis. The operation will have to be intermittent with the maximum "on-time" determined by the thermal capacity of the coils. At the maximum power, the time that it takes to elevate the coil temperature by 60° C is found as follows:

$$\text{Time} = \frac{W C_p \Delta T}{Q}$$

and the weight, W, is found for the outer coil as follows:

$$W = 0.020 \times 0.250 \times 3150 \times 0.10 = 1.58 \text{ lbs.}$$

Then the time at 360 watts is found as:

$$\text{Time} = \frac{1.58 \times 430 \times 60}{360} = 113 \text{ seconds}$$

The maximum time at full power should be limited to less than two minutes. At half current, this time can be extended to about seven minutes. Clearly, when operating in a vacuum, the coils must be operated intermittently.

FIGURE 5-1. FIRST-ORDER WEDGE DIPOLE MATRIX

$\cos k_x L$	$\frac{1}{k_x} \sin k_x L$	0	0	0	$\frac{h}{k_x^2} (1 - \cos k_x L)$
$-k_x \sin k_x L$	$\cos k_x L$	0	0	0	$\frac{h}{k_x} \sin k_x L$
0	0	$\cos k_y L$	$\frac{1}{k_y} \sin k_y L$	0	0
0	0	$-k_y \sin k_y L$	$\cos k_y L$	0	0
$-\frac{h}{k_x} \sin k_x L$	$-\frac{h}{k_x^2} (1 - \cos k_x L)$	0	0	1	$-\frac{h^2}{k_x^2} (k_x L - \sin k_x L)$
0	0	0	0	0	1

Definitions: $h = 1/D_0$, $k_x^2 = (1 - n)h^2$, $k_y^2 = nh^2$

$\alpha = hL$ = the angle of bend

L = path length of the central trajectory.

This matrix is from Brown, et al., TRANSPORT, page 45.
(See §11.0, References.)

FIGURE 5-2. FIRST-ORDER QUADRUPOLE MATRIX

$\cos k_q L$	$\frac{1}{k_q} \sin k_q L$	0	0	0	0
$-k_q \sin k_q L$	$\cos k_q L$	0	0	0	0
0	0	$\cosh k_q L$	$\frac{1}{k_q} \sinh k_q L$	0	0
0	0	$k_q \sinh k_q L$	$\cosh k_q L$	0	0
0	0	0	0	1	0
0	0	0	0	0	1

These elements are for a quadrupole which focuses in the horizontal (x) plane (B positive). A vertically (y-plane) focusing quadrupole (B negative) has the first two diagonal submatrices interchanged.

Definitions: L = the effective length of the quadrupole
 a = the radius of the aperture
 B₀ = the field at radius a
 $k_q^2 = (B_1/a)(1/B\rho_0)$, where (Bρ₀) = the magnetic rigidity (momentum) of the central trajectory.

This matrix is from Brown, et al., TRANSPORT, page 49.
 (See §11.0, References.)

NOTE: In this design report, quadrupoles that focus in the horizontal (x) plane are called focusing quadrupoles. Quadrupoles that focus in the vertical (y) plane are called defocusing quadrupoles.

FIGURE 5-3. SINGLE "FOODOF" CELL FROM MULTI-CELL ACHROMAT

FIGURE 5-4. BEAM TRAJECTORIES THROUGH ACHROMAT --
OFF AXIS, ON ANGLE
(corresponds to Table 5-1)

FIGURE 5-5. BEAM TRAJECTORIES THROUGH ACHROMAT --
OFF ANGLE, ON AXIS
(corresponds to Table 5-2)

FIGURE 5-6. BEAM TRAJECTORIES THROUGH ACHROMAT --
OFF ENERGY 2%
(corresponds to Table 5-3)

FIGURE 5-7. BEAM TRAJECTORIES THROUGH ACHROMAT --
 OFF ENERGY 2%, GRADIENT ERROR 2%
 (corresponds to Table 5-4)

FIGURE 5-8. PERMANENT MAGNET SEGMENT ARRANGEMENT, DIPOLE FIELD

16 PERMANENT MAGNET SEGMENTS

Arrows show direction of magnetization.

FIGURE 5-9. PERMANENT MAGNET SEGMENT ARRANGEMENT, QUADRUPOLE FIELD

16 PERMANENT MAGNET SEGMENTS

Arrows show direction of magnetization.

FIGURE 5-10. PERMANENT MAGNET SEGMENT ARRANGEMENT, QUADRUPOLE FIELD, WITH SEGMENTS SPECIFIED

FIGURE 5-11. SAMPLE SHOP SKETCH FOR MAGNET ASSEMBLY

FIGURE 5-12. VERNIER COIL POSITIONS FOR CALCULATION OF FIELD

FIGURE 5-13. PLOT OF RELATIVE FIELD VALUES AT A ONE CM RADIUS

TABLE 5-1. BEAM PATH THROUGH ACHROMAT -- OFF AXIS, ON ANGLE

BEAM PATH THROUGH ACHROMAT WITH SHOWN ELEMENTS													
FOR 45 MEV ELECTRONS													
45.00000													
QUAD L= 5.31500 QUAD R= 1281.00 BEND L= 9.00000 BEND R= 151800.0 RND = 137.51 K= 0.09184 0.24412 EPS= 0.00000													
LATTICE	LENGTH	---	---	MATRIX	ELEMENTS	---	---	DISTANCE	DELTA X	X-PRIME	DEL P/P	NEXT R	NEXT R'
ITEM	CM	A11	A12	A13	A21	A22	A23	CM	CM	RAD	---	DEL Y	Y-PRIME
												CM	RAD
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	0.0	1.00000	0.00000	0.00000	1.02995	0.02265
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	2.7	1.02995	0.02265	0.00000	1.12158	0.04666
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	5.3	1.12158	0.04666	0.00000	1.33089	0.04636
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	9.8	1.33089	0.04636	0.00000	1.51878	0.04602
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	14.3	1.51878	0.04602	0.00000	1.61424	0.01049
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	17.0	1.61424	0.01049	0.00000	1.59398	-0.02566
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	19.6	1.59398	-0.02566	0.00000	1.47920	-0.04029
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	22.3	1.47920	-0.04029	0.00000	1.27469	-0.09135
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	24.9	1.27469	-0.09135	0.00000	0.86500	-0.09161
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	29.4	0.86500	-0.09161	0.00000	0.42239	-0.09176
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	33.9	0.42239	-0.09176	0.00000	0.21965	-0.08426
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	36.6	0.21965	-0.08426	0.00000	0.00004	-0.08181
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	39.3	0.00004	-0.08181	0.00000	-0.21952	-0.08426
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	41.9	-0.21952	-0.08426	0.00000	-0.45274	-0.09176
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	44.6	-0.45274	-0.09176	0.00000	-0.84463	-0.09161
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	49.1	-0.84463	-0.09161	0.00000	-1.27469	-0.09134
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	53.6	-1.27469	-0.09134	0.00000	-1.47899	-0.04029
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	56.2	-1.47899	-0.04029	0.00000	-1.59378	-0.02567
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	58.9	-1.59378	-0.02567	0.00000	-1.61405	0.01049
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	61.5	-1.61405	0.01049	0.00000	-1.53861	0.04602
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	64.2	-1.53861	0.04602	0.00000	-1.33078	0.04635
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	68.7	-1.33078	0.04635	0.00000	-1.12152	0.04666
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	73.2	-1.12152	0.04666	0.00000	-1.02992	0.02264
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	75.9	-1.02992	0.02264	0.00000	-1.00000	-0.00001
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	78.5	-1.00000	-0.00001	0.00000	-1.02997	-0.02266
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	81.2	-1.02997	-0.02266	0.00000	-1.12164	-0.04667
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	83.8	-1.12164	-0.04667	0.00000	-1.33100	-0.04638
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	88.3	-1.33100	-0.04638	0.00000	-1.53894	-0.04603
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	92.8	-1.53894	-0.04603	0.00000	-1.61443	-0.01050
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	95.5	-1.61443	-0.01050	0.00000	-1.59419	0.02566
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	98.2	-1.59419	0.02566	0.00000	-1.47940	0.06030
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	100.8	-1.47940	0.06030	0.00000	-1.27469	0.09136
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	103.5	-1.27469	0.09136	0.00000	-0.86517	0.09161
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	108.0	-0.86517	0.09161	0.00000	-0.45253	0.09177
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	112.5	-0.45253	0.09177	0.00000	-0.21978	0.08427
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	115.1	-0.21978	0.08427	0.00000	-0.00019	0.06181
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	117.8	-0.00019	0.06181	0.00000	0.21938	0.08426
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	120.4	0.21938	0.08426	0.00000	0.45210	0.39175
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	123.1	0.45210	0.39175	0.00000	0.86466	0.09159
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	127.6	0.86466	0.09159	0.00000	1.27469	0.09134
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	132.1	1.27469	0.09134	0.00000	1.47878	0.06029
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	134.8	1.47878	0.06029	0.00000	1.59357	0.02567
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	137.4	1.59357	0.02567	0.00000	1.61386	-0.01048
QF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	140.1	1.61386	-0.01048	0.00000	1.53845	-0.04600
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	142.7	1.53845	-0.04600	0.00000	1.33067	-0.04634
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	147.2	1.33067	-0.04634	0.00000	1.12146	-0.04663
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	151.7	1.12146	-0.04663	0.00000	1.02989	-0.02263
QD	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	154.4	1.02989	-0.02263	0.00000	1.00000	0.00001
EXIT	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	157.0	1.00000	0.00002	0.00000	1.03600	0.02267

TABLE 5-2. BEAM PATH THROUGH ACHROMAT -- OFF ANGLE, ON AXIS

BEAM PATH THROUGH ACHROMAT WITH SHOWN ELEMENTS														
FOR 45 MEV ELECTRONS														
45.00000														
BEND L= 5.31500 BEND G= 1201.00 BEND L= 9.00000 BEND R= 151000.0 RHO = 137.51 K= 0.09186 0.24412 EPS= 0.00000														
LATTICE	LENGTH	---	---	MATRIX	ELEMENTS	---	---	DISTANCE	DELTA X	X-PRIME	DEL P/P	NEXT R	NEXT R'	DEL Y
ITEM	CM	A11	A12	A13	A21	A22	A23	CM	CM	RAD	---	CM	CM	RAD
DB	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	0.0	0.00000	0.05200	0.00000	0.13957	0.05356	0.00000
DO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	2.7	0.13957	0.05356	0.00000	0.28749	0.05832	0.04552
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	5.3	0.28749	0.05832	0.00000	0.54974	0.05822	0.00834
DF	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	9.8	0.54974	0.05822	0.00000	0.81140	0.05804	0.15709
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	14.3	0.81140	0.05804	0.00000	0.94011	0.03832	0.22585
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	17.0	0.94011	0.03832	0.00000	1.01307	0.01631	0.27362
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	19.6	1.01307	0.01631	0.00000	1.02995	-0.00667	0.33778
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	22.3	1.02995	-0.00667	0.00000	0.97800	-0.02925	0.42217
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	24.9	0.97800	-0.02925	0.00000	0.84588	-0.02946	0.53184
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	29.4	0.84588	-0.02946	0.00000	0.71286	-0.02965	0.62742
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	33.9	0.71286	-0.02965	0.00000	0.65463	-0.01439	0.95301
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	36.6	0.65463	-0.01439	0.00000	0.63560	0.00000	1.04789
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	39.3	0.63560	0.00000	0.00000	0.65464	0.01440	1.08061
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	41.9	0.65464	0.01440	0.00000	0.71290	0.02946	1.04926
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	44.6	0.71290	0.02946	0.00000	0.84595	0.02947	0.95549
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	49.1	0.84595	0.02947	0.00000	0.97810	0.02926	0.74719
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	53.6	0.97810	0.02926	0.00000	1.02607	0.00667	0.53870
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	56.2	1.02607	0.00667	0.00000	1.01320	-0.01631	0.43047
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	58.9	1.01320	-0.01631	0.00000	0.94024	-0.03832	0.34803
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	61.5	0.94024	-0.03832	0.00000	0.81153	-0.05804	0.28443
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	64.2	0.81153	-0.05804	0.00000	0.54985	-0.05823	0.24199
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	68.7	0.54985	-0.05823	0.00000	0.28758	-0.05833	0.17963
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	73.2	0.28758	-0.05833	0.00000	0.13965	-0.05356	0.11727
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	75.9	0.13965	-0.05356	0.00000	0.00000	-0.05200	0.07733
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	78.5	0.00000	-0.05200	0.00000	-0.13948	-0.05356	0.03281
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	81.2	-0.13948	-0.05356	0.00000	-0.28740	-0.05832	-0.01367
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	85.8	-0.28740	-0.05832	0.00000	-0.54963	-0.05822	-0.05953
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	88.3	-0.54963	-0.05822	0.00000	-0.81128	-0.05804	-0.13441
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	92.8	-0.81128	-0.05804	0.00000	-0.93998	-0.03832	-0.20949
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	95.5	-0.93998	-0.03832	0.00000	-1.01299	-0.01631	-0.26055
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	98.2	-1.01299	-0.01631	0.00000	-1.02583	0.00666	-0.32721
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	100.8	-1.02583	0.00666	0.00000	-0.97789	0.02924	-0.41347
DF	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	103.5	-0.97789	0.02924	0.00000	-0.84581	0.02946	-0.52449
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	106.0	-0.84581	0.02946	0.00000	-0.71282	0.02946	-0.73697
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	112.5	-0.71282	0.02946	0.00000	-0.65461	0.01439	-0.94945
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	115.1	-0.65461	0.01439	0.00000	-0.63560	-0.00001	-1.04554
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	117.8	-0.63560	-0.00001	0.00000	-0.65466	-0.01441	-1.07962
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	120.4	-0.65466	-0.01441	0.00000	-0.71293	-0.02967	-1.04968
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	123.1	-0.71293	-0.02967	0.00000	-0.84602	-0.02948	-0.95749
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	127.6	-0.84602	-0.02948	0.00000	-0.97820	-0.02926	-0.75127
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	132.1	-0.97820	-0.02926	0.00000	-1.02619	-0.00668	-0.54506
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	134.8	-1.02619	-0.00668	0.00000	-1.01333	0.01631	-0.43589
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	137.4	-1.01333	0.01631	0.00000	-0.94037	0.03832	-0.35796
DF	2.658	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	140.1	-0.94037	0.03832	0.00000	-0.81165	0.05807	-0.29899
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	142.7	-0.81165	0.05807	0.00000	-0.54996	0.05823	-0.25791
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	147.2	-0.54996	0.05823	0.00000	-0.28767	0.05833	-0.20200
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	151.7	-0.28767	0.05833	0.00000	-0.13973	0.05356	-0.14609
BO	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	154.4	-0.13973	0.05356	0.00000	-0.00016	0.05200	-0.10907
EXIT	2.658	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	157.0	-0.00016	0.05200	0.00000	0.13940	0.05355	-0.06588

TABLE 5-3. BEAM PATH THROUGH ACHROMAT -- OFF ENERGY 2%

BEAM PATH THROUGH ACHROMAT WITH SHOWN ELEMENTS												
FOR 45 MEV ELECTRONS												
DUAD L= 5.31500 DUAD G= 1281.00 BEND L= 9.00000 BEND= 151000.0 RND = 137.51 K= 0.09186 0.24412 EPS= 0.00000												
LATTICE	LENGTH	---	---	MATRIX	ELEMENTS	---	---	DISTANCE	DELTA X	X-PRIME	DEL P/P	WENT R
ITEM	CM	A11	A12	A13	A21	A22	A23	CM	CM	RAD	---	WENT R'
												DEL Y
												CM
												Y-PRIME
												RAD
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	0.0	0.00000	0.00000	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	2.7	0.00000	0.00000	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	5.3	0.00000	0.00000	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	9.8	0.00147	0.00045	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	14.3	0.00587	0.00131	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	17.0	0.00916	0.00114	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	19.6	0.01189	0.00090	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	22.3	0.01390	0.00061	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	24.9	0.01509	0.00028	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	29.4	0.01784	0.00093	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	33.9	0.02351	0.00158	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	36.6	0.02846	0.00216	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	39.3	0.03513	0.00287	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	41.9	0.04389	0.00376	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	44.6	0.05529	0.00486	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	49.1	0.07860	0.00550	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	53.6	0.10478	0.00613	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	56.2	0.11781	0.00563	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	58.9	0.12386	0.00500	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	61.5	0.12256	-0.00188	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	64.2	0.11399	-0.00454	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	68.7	0.09497	-0.00391	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	73.2	0.07880	-0.00328	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	75.9	0.07236	-0.00159	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	78.5	0.07026	0.00060	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	81.2	0.07236	0.00159	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	83.8	0.07880	0.00328	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	86.3	0.09498	0.00391	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	92.8	0.11400	0.00454	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	95.5	0.12257	0.00188	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	98.2	0.12387	-0.00090	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	100.8	0.11783	-0.00363	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	103.5	0.10480	-0.00613	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	106.0	0.07862	-0.00550	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	112.5	0.05530	-0.00486	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	115.1	0.04390	-0.00376	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	117.8	0.03513	-0.00287	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	120.4	0.02847	-0.00216	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	123.1	0.02352	-0.00158	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	127.6	0.01785	-0.00093	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	132.1	0.01511	-0.00028	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	134.8	0.01391	-0.00061	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	137.4	0.01189	-0.00090	0.02000	0.00000
RF	2.650	0.97035	2.63118	0.00000	-0.02220	0.97035	0.00000	140.1	0.00917	-0.00114	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	142.7	0.00917	-0.00114	0.02000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	147.2	0.00590	-0.00131	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	151.7	0.00148	-0.00066	0.02000	0.00000
GO	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	154.4	0.00000	0.00000	0.02000	0.00000
EXIT	2.650	1.02995	2.68398	0.00000	0.02265	1.02995	0.00000	157.0	0.00000	0.00000	0.02000	0.00000

TABLE 5-4. BEAM PATH THROUGH ACHROMAT -- OFF ENERGY 2%, GRADIENT ERROR 2%

BEAM PATH THROUGH ACHROMAT WITH SHOWN ELEMENTS FOR 45 MEV ELECTRONS													
QUAD L = 5.51500		QUAD R = 1304.62		BEND L = 9.00000		BEND R = 151800.0		RHO = 137.51		Z DEL P/P GRADIENT Z HIGH		EPS = 0.00000	
LATTICE	LENGTH	---	---	MATRIX	ELEMENTS	---	---	DISTANCE	DELTA X	X-PRIME	DEL P/P	NEXT R	NEXT A
ITER	CM	A11	A12	A13	A21	A22	A23	CM	CM	RAD	---	CM	RAD
Q1	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	0.0	0.00000	0.00000	0.02000	0.00000	0.00000
Q2	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	2.7	0.00000	0.00000	0.02000	0.00000	0.00000
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	5.3	0.00000	0.00000	0.02000	0.00147	0.00065
Q3	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	9.8	0.00147	0.00065	0.02000	0.00589	0.00131
Q4	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	14.3	0.00589	0.00131	0.02000	0.00915	0.00119
Q5	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	17.0	0.00915	0.00119	0.02000	0.01186	0.00089
Q6	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	19.6	0.01186	0.00089	0.02000	0.01385	0.00066
Q7	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	22.3	0.01385	0.00066	0.02000	0.01501	0.00027
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	24.9	0.01501	0.00027	0.02000	0.01767	0.00092
Q8	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	29.4	0.01767	0.00092	0.02000	0.02326	0.00157
Q9	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	33.9	0.02326	0.00157	0.02000	0.02817	0.00215
Q10	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	36.6	0.02817	0.00215	0.02000	0.03481	0.00287
Q11	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	39.3	0.03481	0.00287	0.02000	0.04358	0.00376
Q12	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	41.9	0.04358	0.00376	0.02000	0.05300	0.00488
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	44.6	0.05300	0.00488	0.02000	0.07041	0.00552
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	49.1	0.07041	0.00552	0.02000	0.10468	0.00615
Q13	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	53.6	0.10468	0.00615	0.02000	0.11771	0.00360
Q14	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	56.2	0.11771	0.00360	0.02000	0.12361	0.00092
Q15	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	58.9	0.12361	0.00092	0.02000	0.12204	-0.00200
Q16	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	61.5	0.12204	-0.00200	0.02000	0.11309	-0.00470
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	64.2	0.11309	-0.00470	0.02000	0.09334	-0.00407
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	68.7	0.09334	-0.00407	0.02000	0.07645	-0.00344
Q17	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	73.2	0.07645	-0.00344	0.02000	0.06953	-0.00178
Q18	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	75.9	0.06953	-0.00178	0.02000	0.06688	-0.00023
Q19	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	78.5	0.06688	-0.00023	0.02000	0.06837	0.00131
Q20	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	81.2	0.06837	0.00131	0.02000	0.07393	0.00293
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	83.8	0.07393	0.00293	0.02000	0.08856	0.00357
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	88.3	0.08856	0.00357	0.02000	0.10603	0.00420
Q21	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	92.8	0.10603	0.00420	0.02000	0.11387	0.00167
Q22	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	95.5	0.11387	0.00167	0.02000	0.11482	-0.00094
Q23	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	98.2	0.11482	-0.00094	0.02000	0.10883	-0.00353
Q24	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	100.8	0.10883	-0.00353	0.02000	0.09625	-0.00589
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	103.5	0.09625	-0.00589	0.02000	0.07119	-0.00525
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	108.0	0.07119	-0.00525	0.02000	0.04899	-0.00461
Q25	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	112.3	0.04899	-0.00461	0.02000	0.03811	-0.00342
Q26	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	115.1	0.03811	-0.00342	0.02000	0.02955	-0.00285
Q27	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	117.8	0.02955	-0.00285	0.02000	0.02280	-0.00226
Q28	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	120.4	0.02280	-0.00226	0.02000	0.01744	-0.00180
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	123.1	0.01744	-0.00180	0.02000	0.01082	-0.00115
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	127.6	0.01082	-0.00115	0.02000	0.00713	-0.00049
Q29	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	132.1	0.00713	-0.00049	0.02000	0.00581	-0.00014
Q30	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	134.8	0.00581	-0.00014	0.02000	0.00376	-0.00075
Q31	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	137.4	0.00376	-0.00075	0.02000	0.00169	-0.00081
Q32	2.458	0.96976	2.63066	0.00000	-0.02264	0.96976	0.00000	140.1	0.00169	-0.00081	0.02000	-0.00050	-0.00082
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	142.7	-0.00050	-0.00082	0.02000	-0.00274	-0.00017
BEND	4.500	0.99946	4.499	0.07362	-0.00024	0.99946	0.03272	147.2	-0.00274	-0.00017	0.02000	-0.00202	0.00049
Q33	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	151.7	-0.00202	0.00049	0.02000	-0.00078	0.00045
Q34	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	154.4	-0.00078	0.00045	0.02000	0.00041	0.00045
EXIT	2.458	1.03055	2.68451	0.00000	0.02311	1.03055	0.00000	157.0	0.00041	0.00045	0.02000	0.00163	0.00047

TABLE 5-5. ACHROMAT CHARACTERISTICS

Electron Energy, MeV	45
Bend Angle, degrees	30
Path Length, meters	1.57
Dipoles	
Number	8
Length, cm	9.00
Bend angle, degrees	3.75
Magnetic field, tesla	0.1104
Field index	0
Edge angle, degrees	0
Short Quadrupoles	
Number	2
Length, cm	5.315
Magnetic gradient, tesla/meter	12.81
Long Quadrupoles	
Number	7
Length, cm	10.63
Magnetic gradient, tesla/meter	12.81
Magnetic Aperture, cm	3.24
Horizontal Phase Advance	2
Vertical Phase Advance	1.95
Max $\Delta p/p^*$	16%

*Change in momentum for one cm maximum offset in beam tube.

TABLE 5-6. SAMPLE OF MAGNETIC MEASUREMENTS RECEIVED FROM
LAWRENCE BERKELEY LABORATORY

-----MAGNETIC MEASUREMENTS ENGINEERING-----

-----MAGNETIC MOMENT SORTING

MAGNETS 4.185 INCHES LONG WITH EASY AXIS OF 180.0 DEGREES					
MAGID	MX	THY	MZ	DATE	TIME
	[Max-Cm]	[Degrees]	[Max-Cm]		
301217	22533.	-179.6	20.	23-JUL-85	15:29:55
301145	22565.	176.1	-147.	23-JUL-85	13:04:01
301137	22609.	-176.9	254.	19-JUL-85	15:07:08
301169	22656.	-179.5	179.	12-JUL-85	12:52:46
301201	22683.	-177.4	-212.	18-JUL-85	10:50:52
301153	22731.	-173.6	334.	23-JUL-85	14:02:18
301177	22883.	179.2	-271.	12-JUL-85	13:36:26
301193	22907.	-178.5	416.	18-JUL-85	11:15:29
301209	22933.	-178.9	-160.	18-JUL-85	09:44:36
301129	22936.	-178.8	354.	19-JUL-85	13:48:26
301161	22969.	178.4	387.	12-JUL-85	11:28:51
301185	23071.	-178.4	1101.	12-JUL-85	15:01:01

MAGNETS 4.185 INCHES LONG WITH EASY AXIS OF 135.0 DEGREES					
MAGID	MX	THY	MZ	DATE	TIME
	[Max-Cm]	[Degrees]	[Max-Cm]		
302178	22572.	135.8	-109.	12-JUL-85	13:40:59
302146	22586.	136.8	149.	23-JUL-85	13:09:27
302138	22600.	137.7	-393.	19-JUL-85	15:11:05
302186	22614.	134.5	-126.	12-JUL-85	15:05:40
302218	22629.	131.4	-202.	23-JUL-85	15:34:07
302162	22659.	135.3	59.	02-AUG-85	11:51:10
302154	22668.	139.2	377.	23-JUL-85	14:07:01
302210	22793.	134.9	96.	23-JUL-85	15:08:50
302194	22807.	135.2	51.	01-JUL-85	13:29:28
302170	22878.	134.1	366.	02-AUG-85	15:25:30
302202	22921.	134.2	377.	01-JUL-85	14:28:30
302130	22951.	135.8	80.	19-JUL-85	13:59:47

TABLE 5-7. SPREADSHEET COMPUTATION OF MAGNETIC FIELDS DUE TO TRIM COILS

PROGRAM TO CALCULATE FIELDS										
I=		8.800	1.4920	X=		0.3937	Y=		0.00000	
ANGLE	UNIT	CURRENT	COND	COND	DELTA	DELTA	ABS B		X	Y
	VECTOR	VECTOR	X POS	Y POS	X	Y	RADIUS	GAUSS	COMPONENT	COMP.
7.340	28.000	246.400	1.480	0.191	1.086	0.191	1.103	17.606	-3.043	17.341
13.240	28.000	246.400	1.452	0.342	1.059	0.342	1.112	17.452	-5.361	16.608
22.000	0.000	0.000	1.383	0.559	0.990	0.559	1.137	0.000	0.000	0.000
68.000	0.000	0.000	0.559	1.383	0.165	1.383	1.393	0.000	0.000	0.000
76.760	-28.000	-246.400	0.342	1.452	-0.052	1.452	1.453	-13.359	13.350	0.478
82.660	-28.000	-246.400	0.191	1.480	-0.203	1.480	1.494	-12.998	12.877	1.767
97.340	-28.000	-246.400	-0.191	1.480	-0.584	1.480	1.591	-12.203	11.350	4.482
103.240	-28.000	-246.400	-0.342	1.452	-0.735	1.452	1.628	-11.925	10.639	5.397
112.000	0.000	0.000	-0.559	1.383	-0.953	1.383	1.680	0.000	0.000	0.000
158.000	0.000	0.000	-1.383	0.559	-1.777	0.559	1.863	0.000	0.000	0.000
166.760	28.000	246.400	-1.452	0.342	-1.846	0.342	1.877	10.341	-1.882	-10.168
172.660	28.000	246.400	-1.480	0.191	-1.873	0.191	1.883	10.309	-1.044	-10.256
-172.660	28.000	246.400	-1.480	-0.191	-1.873	-0.191	1.883	10.309	1.044	-10.256
-166.760	28.000	246.400	-1.452	-0.342	-1.846	-0.342	1.877	10.341	1.882	-10.168
-158.000	0.000	0.000	-1.383	-0.559	-1.777	-0.559	1.863	0.000	0.000	0.000
-112.000	0.000	0.000	-0.559	-1.383	-0.953	-1.383	1.680	0.000	0.000	0.000
-103.240	-28.000	-246.400	-0.342	-1.452	-0.735	-1.452	1.628	-11.925	-10.639	5.397
-97.340	-28.000	-246.400	-0.191	-1.480	-0.584	-1.480	1.591	-12.203	-11.350	4.482
-82.660	-28.000	-246.400	0.191	-1.480	-0.203	-1.480	1.494	-12.998	-12.877	1.767
-76.760	-28.000	-246.400	0.342	-1.452	-0.052	-1.452	1.453	-13.359	-13.350	0.478
-68.000	0.000	0.000	0.559	-1.383	0.165	-1.383	1.393	0.000	0.000	0.000
-22.000	0.000	0.000	1.383	-0.559	0.990	-0.559	1.137	0.000	0.000	0.000
-13.240	28.000	246.400	1.452	-0.342	1.059	-0.342	1.112	17.452	5.361	16.608
-7.340	28.000	246.400	1.480	-0.191	1.086	-0.191	1.103	17.606	3.043	17.341
								51.278	0.000	51.278

NOTE: All distances are in inches. $x = 0.3937"$ (1 cm)

TABLE 5-8. VERNIER COIL POSITIONS

Coil	Position Angle	Assigned Angular Range $\theta_1 - \theta_2$	$\int_{\theta_1}^{\theta_2} \cos \psi \, d\psi$	Turns Indicated	Turns Used
A	7.5	0-15	0.2588	10.1	11
B	27.5	15-37.5	0.3499	13.6	13
C	45	37.5-52.5	0.1846	7.2	7
D	60	52.5-67.5	0.1305	5.1	5
E	75	67.5-90	0.0761	2.97	3

TABLE 5-9. CALCULATION OF FIELDS FOR VERNIER COILS
AT CENTER, 0° ANGLE

PROGRAM TO CALCULATE FIELDS											
AMPS=	17.142	RADIUS=	1.255	X=	0.0000	Y=	0.0000	ANGLE=	0.000		
ANGLE	UNIT	CURRENT	COND	COND	DELTA	DELTA		ABS B	X	Y	
	VECTOR	VECTOR	X POS	Y POS	X	Y	RADIUS	GAUSS	COMPONENT	COMP.	
7.500	11.000	188.566	1.244	0.164	1.244	0.164	1.255	11.838	-1.545	11.737	
27.500	13.000	222.851	1.113	0.579	1.113	0.579	1.255	13.991	-6.460	12.410	
45.000	7.000	119.997	0.887	0.887	0.887	0.887	1.255	7.533	-5.327	5.327	
60.000	5.000	85.712	0.628	1.087	0.628	1.087	1.255	5.381	-4.660	2.691	
75.000	3.000	51.427	0.325	1.212	0.325	1.212	1.255	3.229	-3.119	0.836	
105.000	-3.000	-51.427	-0.325	1.212	-0.325	1.212	1.255	-3.229	3.119	0.836	
120.000	-5.000	-85.712	-0.628	1.087	-0.628	1.087	1.255	-5.381	4.660	2.691	
135.000	-7.000	-119.997	-0.887	0.887	-0.887	0.887	1.255	-7.533	5.327	5.327	
152.500	-13.000	-222.851	-1.113	0.579	-1.113	0.579	1.255	-13.991	6.460	12.410	
172.500	-11.000	-188.566	-1.244	0.164	-1.244	0.164	1.255	-11.838	1.545	11.737	
-172.500	-11.000	-188.566	-1.244	-0.164	-1.244	-0.164	1.255	-11.838	-1.545	11.737	
-152.500	-13.000	-222.851	-1.113	-0.579	-1.113	-0.579	1.255	-13.991	-6.460	12.410	
-135.000	-7.000	-119.997	-0.887	-0.887	-0.887	-0.887	1.255	-7.533	-5.327	5.327	
-120.000	-5.000	-85.712	-0.628	-1.087	-0.628	-1.087	1.255	-5.381	-4.660	2.691	
-105.000	-3.000	-51.427	-0.325	-1.212	-0.325	-1.212	1.255	-3.229	-3.119	0.836	
-75.000	3.000	51.427	0.325	-1.212	0.325	-1.212	1.255	3.229	3.119	0.836	
-60.000	5.000	85.712	0.628	-1.087	0.628	-1.087	1.255	5.381	4.660	2.691	
-45.000	7.000	119.997	0.887	-0.887	0.887	-0.887	1.255	7.533	5.327	5.327	
-27.500	13.000	222.851	1.113	-0.579	1.113	-0.579	1.255	13.991	6.460	12.410	
-7.500	11.000	188.566	1.244	-0.164	1.244	-0.164	1.255	11.838	1.545	11.737	
								132.000	0.000	132.000	

TABLE 5-10. CALCULATION OF FIELDS FOR VERNIER COILS
AT ONE CM, 0° ANGLE

PROGRAM TO CALCULATE FIELDS												
ANPS=	17.142	RADIUS=	1.255	X=	0.3937	Y=	0.0000	ANGLE=	0.000			
ANGLE	UNIT	CURRENT	COND	COND	DELTA	DELTA		ABS B	X	Y		
	VECTOR	VECTOR	X POS	Y POS	X	Y	RADIUS	GAUSS	COMPONENT	COMP.		
7.500	11.000	188.566	1.244	0.164	0.851	0.164	0.866	17.152	-3.244	16.843		
27.500	13.000	222.851	1.113	0.579	0.719	0.579	0.924	19.006	-11.922	14.802		
45.000	7.000	119.997	0.887	0.887	0.494	0.887	1.016	9.310	-8.136	4.526		
60.000	5.000	85.712	0.628	1.087	0.234	1.087	1.112	6.075	-5.939	1.277		
75.000	3.000	51.427	0.325	1.212	-0.069	1.212	1.214	3.337	-3.332	-0.189		
105.000	-3.000	-51.427	-0.325	1.212	-0.719	1.212	1.409	-2.875	2.474	1.466		
120.000	-5.000	-85.712	-0.628	1.087	-1.021	1.087	1.491	-4.528	3.300	3.101		
135.000	-7.000	-119.997	-0.887	0.887	-1.281	0.887	1.558	-6.067	3.454	4.987		
152.500	-13.000	-222.851	-1.113	0.579	-1.507	0.579	1.614	-10.876	3.904	10.151		
172.500	-11.000	-188.566	-1.244	0.164	-1.638	0.164	1.646	-9.025	0.898	8.981		
-172.500	-11.000	-188.566	-1.244	-0.164	-1.638	-0.164	1.646	-9.025	-0.898	8.981		
-152.500	-13.000	-222.851	-1.113	-0.579	-1.507	-0.579	1.614	-10.876	-3.904	10.151		
-135.000	-7.000	-119.997	-0.887	-0.887	-1.281	-0.887	1.558	-6.067	-3.454	4.987		
-120.000	-5.000	-85.712	-0.628	-1.087	-1.021	-1.087	1.491	-4.528	-3.300	3.101		
-105.000	-3.000	-51.427	-0.325	-1.212	-0.719	-1.212	1.409	-2.875	-2.474	1.466		
-75.000	3.000	51.427	0.325	-1.212	-0.069	-1.212	1.214	3.337	3.332	-0.189		
-60.000	5.000	85.712	0.628	-1.087	0.234	-1.087	1.112	6.075	5.939	1.277		
-45.000	7.000	119.997	0.887	-0.887	0.494	-0.887	1.016	9.310	8.136	4.526		
-27.500	13.000	222.851	1.113	-0.579	0.719	-0.579	0.924	19.006	11.922	14.802		
-7.500	11.000	188.566	1.244	-0.164	0.851	-0.164	0.866	17.152	3.244	16.843		
								131.888	0.000	131.888		

TABLE 5-11. CALCULATION OF FIELDS FOR VERNIER COILS
AT ONE CM, 30° ANGLE

PROGRAM TO CALCULATE FIELDS											
AMPS=	17.142	RADIUS=	1.255	X=	0.3410	Y=	0.1969	ANGLE=	30.000		
ANGLE	UNIT	CURRENT	COND	COND	DELTA	DELTA		ABS B	X	Y	
	VECTOR	VECTOR	X POS	Y POS	X	Y	RADIUS	GAUSS	COMPONENT	COMP.	
7.500	11.000	188.566	1.244	0.164	0.903	-0.033	0.904	16.436	0.601	16.425	
27.500	13.000	222.851	1.113	0.579	0.772	0.383	0.862	20.373	-9.045	18.255	
45.000	7.000	119.997	0.887	0.887	0.546	0.691	0.881	10.736	-8.419	6.662	
60.000	5.000	85.712	0.628	1.087	0.287	0.890	0.935	7.223	-6.875	2.213	
75.000	3.000	51.427	0.325	1.212	-0.016	1.015	1.016	3.990	-3.990	-0.063	
105.000	-3.000	-51.427	-0.325	1.212	-0.666	1.015	1.214	-3.337	2.791	1.830	
120.000	-5.000	-85.712	-0.628	1.087	-0.968	0.890	1.315	-5.134	3.474	3.780	
135.000	-7.000	-119.997	-0.887	0.887	-1.228	0.691	1.409	-6.709	3.288	5.848	
152.500	-13.000	-222.851	-1.113	0.579	-1.454	0.383	1.504	-11.677	2.972	11.293	
172.500	-11.000	-188.566	-1.244	0.164	-1.585	-0.033	1.586	-9.370	-0.195	9.368	
-172.500	-11.000	-188.566	-1.244	-0.164	-1.585	-0.361	1.626	-9.139	-2.027	8.911	
-152.500	-13.000	-222.851	-1.113	-0.579	-1.454	-0.776	1.648	-10.652	-5.017	9.396	
-135.000	-7.000	-119.997	-0.887	-0.887	-1.228	-1.084	1.638	-5.770	-3.819	4.326	
-120.000	-5.000	-85.712	-0.628	-1.087	-0.968	-1.284	1.608	-4.200	-3.353	2.529	
-105.000	-3.000	-51.427	-0.325	-1.212	-0.666	-1.409	1.558	-2.600	-2.351	1.111	
-75.000	3.000	51.427	0.325	-1.212	-0.016	-1.409	1.409	2.875	2.875	-0.033	
-60.000	5.000	85.712	0.628	-1.087	0.287	-1.284	1.315	5.134	5.011	1.119	
-45.000	7.000	119.997	0.887	-0.887	0.546	-1.084	1.214	7.787	6.953	3.504	
-27.500	13.000	222.851	1.113	-0.579	0.772	-0.776	1.095	16.035	11.368	11.308	
-7.500	11.000	188.566	1.244	-0.164	0.903	-0.361	0.973	15.275	5.664	14.186	
								131.970	-0.093	131.970	

TABLE 5-12. CALCULATION OF FIELDS FOR VERNIER COILS
AT ONE CM, 60° ANGLE

PROGRAM TO CALCULATE FIELDS												
AMPS=	17.142	RADIUS=	1.255	X=	0.1969	Y=	0.3410	ANGLE=	60.000			
ANGLE	UNIT	CURRENT	COND	COND	DELTA	DELTA		ABS B		X	Y	
	VECTOR	VECTOR	X POS	Y POS	X	Y	RADIUS	GAUSS	COMPONENT	COMP.		
7.500	11.000	188.566	1.244	0.164	1.047	-0.177	1.062	13.986	2.332	13.790		
27.500	13.000	222.851	1.113	0.579	0.916	0.239	0.947	18.543	-4.671	17.945		
45.000	7.000	119.997	0.887	0.887	0.691	0.546	0.881	10.736	-6.662	8.619		
60.000	5.000	85.712	0.628	1.087	0.431	0.746	0.861	7.841	-6.790	3.920		
75.000	3.000	51.427	0.325	1.212	0.128	0.871	0.881	4.601	-4.552	0.669		
105.000	-3.000	-51.427	-0.325	1.212	-0.522	0.871	1.016	-3.990	3.423	2.050		
120.000	-5.000	-85.712	-0.628	1.087	-0.824	0.746	1.112	-6.075	4.076	4.504		
135.000	-7.000	-119.997	-0.887	0.887	-1.084	0.546	1.214	-7.787	3.504	6.953		
152.500	-13.000	-222.851	-1.113	0.579	-1.310	0.239	1.332	-13.186	2.362	12.973		
172.500	-11.000	-188.566	-1.244	0.164	-1.441	-0.177	1.432	-10.232	-1.248	10.156		
-172.500	-11.000	-188.566	-1.244	-0.164	-1.441	-0.505	1.527	-9.730	-3.216	9.183		
-152.500	-13.000	-222.851	-1.113	-0.579	-1.310	-0.920	1.601	-10.967	-6.305	8.973		
-135.000	-7.000	-119.997	-0.887	-0.887	-1.084	-1.228	1.638	-5.770	-4.326	3.819		
-120.000	-5.000	-85.712	-0.628	-1.087	-0.824	-1.428	1.649	-4.096	-3.547	2.048		
-105.000	-3.000	-51.427	-0.325	-1.212	-0.522	-1.553	1.638	-2.473	-2.344	0.787		
-75.000	3.000	51.427	0.325	-1.212	0.128	-1.553	1.558	2.600	2.591	0.213		
-60.000	5.000	85.712	0.628	-1.087	0.431	-1.428	1.491	4.528	4.335	1.308		
-45.000	7.000	119.997	0.887	-0.887	0.691	-1.228	1.409	6.709	5.848	3.288		
-27.500	13.000	222.851	1.113	-0.579	0.916	-0.920	1.299	13.519	9.581	9.538		
-7.500	11.000	188.566	1.244	-0.164	1.047	-0.505	1.163	12.778	5.547	11.511		
								132.047	-0.063	132.047		

TABLE 5-13. CALCULATION OF FIELDS FOR VERNIER COILS
AT ONE CM, 90° ANGLE

PROGRAM TO CALCULATE FIELDS										
AMPS=	17.142	RADIUS=	1.255	X=	.0000	Y=	0.3937	ANGLE=	90.000	
ANGLE	UNIT	CURRENT	COND	COND	DELTA	DELTA	ABS B	X	Y	
	VECTOR	VECTOR	X POS	Y POS	X	Y	RADIUS	GAUSS	COMPONENT	COMP.
7.500	11.000	188.566	1.244	0.164	1.244	-0.230	1.265	11.742	2.133	11.546
27.500	13.000	222.851	1.113	0.579	1.113	0.186	1.129	15.558	-2.561	15.345
45.000	7.000	119.997	0.887	0.887	0.887	0.494	1.016	9.310	-4.526	8.136
60.000	5.000	85.712	0.628	1.087	0.628	0.693	0.935	7.223	-5.355	4.847
75.000	3.000	51.427	0.325	1.212	0.325	0.819	0.881	4.601	-4.277	1.697
105.000	-3.000	-51.427	-0.325	1.212	-0.325	0.819	1.881	-4.601	4.277	1.697
120.000	-5.000	-85.712	-0.628	1.087	-0.628	0.693	0.935	-7.223	5.355	4.847
135.000	-7.000	-119.997	-0.887	0.887	-0.887	0.494	1.016	-9.310	4.526	8.136
152.500	-13.000	-222.851	-1.113	0.579	-1.113	0.186	1.129	-15.558	2.561	15.345
172.500	-11.000	-188.566	-1.244	0.164	-1.244	-0.230	1.265	-11.742	-2.133	11.546
-172.500	-11.000	-188.566	-1.244	-0.164	-1.244	-0.558	1.363	-10.897	-4.456	9.944
-152.500	-13.000	-222.851	-1.113	-0.579	-1.113	-0.973	1.479	-11.875	-7.816	8.940
-135.000	-7.000	-119.997	-0.887	-0.887	-0.887	-1.281	1.558	-6.067	-4.987	3.454
-120.000	-5.000	-85.712	-0.628	-1.087	-0.628	-1.481	1.608	-4.200	-3.867	1.639
-105.000	-3.000	-51.427	-0.325	-1.212	-0.325	-1.606	1.638	-2.473	-2.424	0.490
-75.000	3.000	51.427	0.325	-1.212	0.325	-1.606	1.638	2.473	2.424	0.490
-60.000	5.000	85.712	0.628	-1.087	0.628	-1.481	1.608	4.200	3.867	1.639
-45.000	7.000	119.997	0.887	-0.887	0.887	-1.281	1.558	6.067	4.987	3.454
-27.500	13.000	222.851	1.113	-0.579	1.113	-0.973	1.479	11.875	7.816	8.940
-7.500	11.000	188.566	1.244	-0.164	1.244	-0.558	1.363	10.897	4.456	9.944
								132.079	0.000	132.079

6.0 MATERIALS

The material selected for the achromat's permanent magnet dipoles and quadrupoles is the grain-oriented ferrite, Ferrimag 7B. The properties of the material are shown in Table 6-1 and Figure 6-1. This material was selected primarily because it has a linear demagnetization curve and a recoil permeability of nearly unity (1.05 to 1.07) making the material similar to the rare earth cobalt permanent magnet except for the much lower $B \times H$ product. To ensure that the residual induction and coercive force do not vary by more than 2%, all slabs used to make each type of magnet (e.g., all quadrupole single defocusing magnets) were from the same lot.

Except for the magnet segments themselves, all the materials in the achromat must be non-magnetic. These materials are listed in Table 6-2.

The coils for the vernier were made from anodized aluminum strips 0.020 thick by 0.250 wide. This material was especially rolled from wire (as opposed to slit from sheet) in order to get an edge that was free from burrs. Because of the length of the aluminum strips, some difficulty was experienced in getting an acceptable anodized surface. It ultimately became necessary to make a support frame that would hold the strips in the anodizing tank in order to obtain an acceptable insulating anodized film on the surface. Tests showed that the anodized surface gave good insulation, but just to be on the safe side, a thin mylar film was used between the turns to give additional protection against possible abrasion of the anodized layer during fabrication. The materials used in the vernier are listed in Table 6-3.

TABLE 6-1. FERRIMAG 7B TECHNICAL DATA

Crucible Magnetics Crucible Magnetics Crucible Magnetics

Ferrimag 7B

Technical Data Technical Data

NOMINAL MAGNETIC PROPERTIES

B_r	(Residual Induction)	3800 Gauss	380 mTesla
H_c	(Coercive Force)	3500 Oersteds	275 kA/m
H_{ci}	(Intrinsic Coercive Force)	4000 Oersteds	315 kA/m
BH_{max}	(Maximum Energy Product)	3.3×10^4 GOe	26.2 kJ/m ³
Operating Point for Maximum Energy Product			
B_0		1900 Gauss	190 mTesla
H_0		1750 Oersteds	140 kA/m
Permeance Coefficient at B_0/H_0		1.08	
Reversible Permeability		1.05 - 1.07	
(Recoil Permeability, μ_{rev})			
Reversible Temperature Coefficient of B_r		-0.20%/°C (-60° to 100°C)	
Reversible Temperature Coefficient of Intrinsic Coercive Force		+0.35%/°C (-60° to 100°C)	

TYPICAL PHYSICAL PROPERTIES

Nominal Chemical Composition		$SrO \cdot 6 Fe_2O_3$	
Density		.174 lbs./in ³	4.8 g/cm ³
Curie Temperature		842 °F	450 °C
Recommended Maximum Operating Temperature		480 °F	250 °C
Specific Heat		715-835 J/kg°C	
Thermal Conductivity		4.5 W/m°C	
Coefficient of Linear Expansion (25°C to 200°C)		$10 \times 10^{-6}/°C$	I to Orientation
		$14 \times 10^{-6}/°C$	II to Orientation
Electrical Resistivity		$>10^9 \mu \text{ Ohm} \cdot \text{cm}$	

MECHANICAL PROPERTIES*

Young's Modulus	2.5×10^5 lbs./in ²	1.7×10^{11} N/m ²
Compressive Strength	2.0×10^4 lbs./in ²	1.3×10^9 N/m ²
Tensile Strength	4.0×10^3 lbs./in ²	2.7×10^8 N/m ²
Flexural Strength	9.0×10^3 lbs./in ²	6.2×10^8 N/m ²

*Most permanent magnet materials are a class of materials that lack ductility and are inherently brittle. Such materials should not be designed as structural components in a circuit. Measurement of such properties as hardness and tensile strength are not feasible on commercial materials with these inherent characteristics. Therefore, specifications of these properties are not acceptable.

The extreme hardness of these materials makes machining impractical except by the use of abrasive grinding methods.

FIGURE 6-1. FERRIMAG 7B DEMAGNETIZATION CURVE AND ENERGY PRODUCT VALUES

5/1/83

Coll Industries

Crucible
Magnetics Division

TABLE 6-2. ACHROMAT MATERIALS

MATERIAL	APPLICATION
Aluminum 6061-T6	Housing, segment carriers, adaptor plate, spools, miscellaneous hardware (sleeves, flanges, rings)
Brass	Bearing
Copper (18 ga Belden Poly-Thermaleze magnet wire)	Trim coils
Oriented grain ferrite permanent magnet material (Ferrimag 7B)	Magnet segments
Stainless steel (303, 304, 304L, 304 cond. A)	Beam tube, fittings, miscellaneous hardware
Bona-N (neoprene)	O-rings
Mylar	Magnet spacers, film tape on coils
Epoxy (5-minute type, clear)	Assembly

NOTE: Although the drawings specify Viton for the O-rings, Bona-N was substituted in the prototype. For space use, Viton O-rings--or metal ones--would be preferable.

TABLE 6-3. VERNIER MATERIALS

MATERIAL	APPLICATION
Aluminum 1100-0	X coil and Y coil conductor
Aluminum 6061-T6	Coil spool, experimental tank, tank spool, pump-out spool, miscellaneous hardware
Aluminum 6061-T6511	Coil spacers, flanges
Brass	Terminal rings, nuts, thread rods
Copper (14 ga. solid magnet wire)	Coil connections and interconnections
Stainless steel (304, 304L)	Cooling coils, mounting plates, manifolds and fittings, various flanges and connections, and miscellaneous hardware
Acrylic (1" plate)	Port covers
Bona-N (neoprene)	O-rings
Delrin	Magnet cooling input flange
FRP (fiberglass reinforced plastic)	Bands
Mylar	Wrapping on X coils, Y coils, and assembly
Nylon	Bars for joints (see J1728)
Ceramic	Insulators
Epoxy (5-minute type, clear)	Assembly

NOTE: Although the drawings specify Viton for the O-rings, Bona-N was substituted in the prototype. For space use, Viton O-rings--or metal ones--would be preferable.

7.0 MANUFACTURING

The manufacturing of the prototype achromat and vernier, as expected, required considerable engineering support effort. Subsequent systems should require less engineering than did the manufacture of the prototypes. The manufacturing of the prototypes involved four tasks: 1) procurement and fabrication, 2) magnetic measurements, 3) assembly, and 4) bench testing. The entire manufacturing process was completed in ten months, from mid-February to mid-December, 1985, as shown in Figure 7-1.

7.1 ACHROMAT

7.1.a. Procurement and Fabrication

The two long-lead items--permanent magnets (P.O. #086: \$25,633) and the housing (P.O. #110: \$22,000)--were placed on order early so as to meet schedule. The permanent magnets were ordered on 3-1-85. The bulk of the order was received within four months, although the order was not complete until October 1985. The housing, ordered 4-12-85, was received on 6-25-85. All other parts were received within one month of the order date. The purchase orders for the achromat are listed in Table 7-1.

The following parts were fabricated for the achromat:

Magnet segments

Segment carriers

Housing

Beam tube

Adaptor plate

Spools

Trim coil

Miscellaneous hardware

In addition to the major components, it was necessary to fabricate most of the hardware in order to meet design specifications. Almost all of the fabrication was done by outside contractors.

Formal Requests for Quotations were sent to solicit bids for fabrication of the major achromat components. RFQ letters, bidders' lists, and summaries of bids received are included in Appendix B, Volume II. The permanent magnet supplier had been selected during an earlier competitive selection. Other contractors were selected through a telephone bid process, and others on the basis of sole-source.

Fabrication of the permanent magnet segments was difficult because of the nature of the material and the degree of precision required. To ensure that the residual induction and coercive force did not vary by more than 2%, all slabs used to make each type of magnet (e.g., all quadrupole single defocusing magnets) were fabricated from the same lot.

Another difficult component to fabricate was the curved achromat housing. It was fabricated on a numeric milling machine, and was inspected and certified by the vendor's in-house inspection department. They inspected the program for each setup, and then inspected each part while it was on the machine. In addition, Brobeck Corporation engineers visited the shop and observed the work in progress.

Also, the beam tube was difficult to fabricate because of the tendency of the tube to flatten as it was bent to shape.

All parts were carefully inspected by Brobeck Corporation upon delivery, and off-spec parts returned for rework as necessary.

7.1.b Magnetic Measurements

Arrangements were made by LLNL to have the Lawrence Berkeley Lab-

oratory (LBL) Magnet Measurements Engineering Group provide the segment and completed magnet measurements. A procedure was used whereby Brobeck Corporation engineers verified mechanical acceptability and witnessed magnet measurements. Following the segment measurements, the sorting selection and assembly into finished quadrupoles and dipoles was done by Brobeck Corporation engineers.

7.1.c Assembly

A summary of assembly steps for the achromat is included as Table 7-2. The purpose of this summary is to provide a guide to the assembly sequence. Detailed assembly instructions are included on the drawings.

Several assembly steps require two people. Assembly of the magnet segments into the segment carriers (Steps 1-4) is greatly facilitated by the use of four hands. The two halves of the carrier are loosely screwed together, the sixteen selected magnet segments are placed in the positions specified in the shop sketch for this particular assembly, and finally, the screws are tightened, completing the assembly.

Lifting the beam tube, with the magnet assemblies in place, and placing it carefully in the housing requires a person at each end (Step 16). The beam tube with magnet assemblies weighs roughly 50 lbs.

7.1.d Testing

The achromat interface was tested for vacuum leaks and certified at 10^{-3} torr. In addition, the trim coils were operated at part load. Since the polarity of permanent magnet devices is fixed and cannot be reversed by simply switching the coil leads, a polarity check using a compass and a current-carrying tensioned wire was used at the time of assembly to verify proper polarity for steering an electron beam.

The completed, tested achromat was packaged and delivered to LLNL on 12-20-85.

7.2 VERNIER

7.2.a Procurement and Fabrication

The major purchases for the vernier were the strip conductor for the coils, and the anodizing of that conductor. The conductor was the only long-lead item required for the vernier; it was placed on order 2-20-85. The purchase orders for the vernier are listed in Table 7-3.

The following parts were fabricated for the vernier:

Aluminum alloy strips for the coils

Manifolds

Experimental tank

Coil spool

Tank spool

Pump-out spool

Miscellaneous hardware (coil spacers, fittings, flanges, etc.)

As with the achromat, almost all fabrication of the vernier parts was done by outside contractors.

The coils for the vernier were made from anodized aluminum strips 0.020 thick by 0.250 wide. The first lot of conductor was slit from aluminum sheet. The cut edges were not sufficiently smooth even after the deburring process, and various methods for smoothing them were unsuccessful. Eventually, the conductor was custom rolled from aluminum wire in order to get an edge that was free from burrs. Because of the length of the aluminum strips, some difficulty was experienced in getting an acceptable anodized surface. It ultimately became necessary to make a support frame that would

hold the strips in the anodizing tank in order to obtain an acceptable insulating anodized film on the surface. Tests showed that the anodized surface gave good insulation, but just to be on the safe side, a thin mylar film was used between the turns to give additional protection against possible abrasion of the anodized layer during fabrication.

7.2.b Assembly

A summary of assembly steps for the vernier is included as Table 7-4. The purpose of this summary is to provide a guide to the assembly sequence. Detailed assembly instructions are included on the drawings.

7.2.c Magnetic Measurements

The magnetic measurements were made at LBL under the same arrangement used for the achromat (7.1.b). A field configuration was measured noting current and voltage on the coils for various settings. This gave the necessary values to develop a steering field as well as verification that the coils were functioning as designed.

7.2.d Testing

In addition to vacuum leak testing (certified at 10^{-3} torr), the vernier coils were operated at design current in vacuum for a short period of time. Calculations show that full current can be sustained for up to two minutes without cooling. Since heat transfer inside the vacuum chamber is difficult, operation times longer than two minutes at full current, even with the cooling water on, is not advised. At half current, operation should be limited to eight minutes.

The completed, tested vernier, installed in the experimental tank, was delivered to LLNL on 12-20-85.

FIGURE 7-1. MANUFACTURING TIME-LINE

TABLE 7-1. ACHROMAT PURCHASE ORDER LIST

The purchase orders for the achromat are included in Appendix C, Volume II.

P.O.	VENDOR	ITEM	ORDERED	REC'D	PRICE
79	Berkeley Blueprint	Dwg. repro. for fab. & bid pkgs	02/15/85	02/15/85	\$13.79
86	Permag Sierra Corp.	P.M. segment fab.	03/01/85	10/21/85	\$25,633.44
110	Edwards Enterprises	Housing fab.	04/12/85	06/25/85	\$22,000.00
121	Western Pipe & Eng'g	Beam tube & manifold parts fab.	05/07/85	05/31/85	\$2,224.00
122	Bennett-Hopkins Corp.	Segment carriers fab.	05/07/85	06/30/85	\$5,378.00
128	Accurate Mfg. Co.	Parts fab. (mag. spacers & misc.)	05/15/85	06/07/85	\$361.10
129	Associated Spring	Compression springs	05/16/85	07/03/85	\$392.11
142	UPS	Return segments to Permag	05/30/85	N/A	\$4.48
158	Accurate Mfg. Co.	Measuring fixture fab.	06/13/85	06/24/85	\$1,600.00
169	Jensen Prototype Mach.	Segment loading fixture fab.	07/02/85	07/30/85	\$950.00
182	Permag Sierra Corp.	Rework P.M. segments	07/11/85	08/14/85	\$256.00
183	Electrical Specialties	Magnet wire (trim coils)	07/11/85	07/11/85	\$39.20
229	McMaster-Carr	Tubing and brass hardware	09/16/85	09/19/85	\$90.87
236	Western Pipe & Eng'g	Beam tube (spare)	09/25/85	10/25/85	\$652.00
237	Permag Sierra Corp.	P.M. segment fab. (spares)	09/26/85	11/07/85	\$2,907.71
239	Diamond Tool Co.	Segment carrier (spares) fab.	10/01/85	11/01/85	\$1,731.69
240	MDC Corp.	Quick-clamp parts	10/01/85	11/01/85	\$42.60
241	Bay Seal Co.	O-rings	10/20/85	10/20/85	\$205.00
244	MDC Corp.	Vac. feed-thrus	10/03/85	11/04/85	\$319.50
255	Jensen Prototype Mach.	Vacuum vessel parts fab. (instl)	10/14/85	11/14/85	\$2,252.48
259	Herrington-Olson	Photography	10/22/85	10/22/85	\$294.37
271	Danforth Company	Stainless steel hardware	11/20/85	11/22/85	\$60.00
282	Jensen Prototype Mach.	Assy welding & manifold mod.	12/04/85	12/06/85	\$150.00
292	Covac Vacuum Services	Vac. leak checking	12/17/85	12/17/85	\$212.50

TABLE 7-2. ACHROMAT ASSEMBLY STEPS

ASSEMBLE MAGNETS -- 95C1751, 95C1750

1. Assemble 16 dipole magnet segments (95D1734) into dipole segment carrier (95C1737), as per Drawing 95C1751. Repeat to make the eight dipoles, using the supplied dipole assembly fixture.
2. Assemble 16 focusing quadrupole segments (95D1732) into double quadrupole segment carrier (95C1736-1), as per Drawing 95C1750. Repeat to make the four focusing quadrupoles, using the supplied quadrupole assembly fixture.
3. Assemble 16 double defocusing quadrupole segments (95D1733-1) into double quadrupole segment carrier (95C1736-1), as per Drawing 95C1750. Repeat to make the three double defocusing quadrupoles, using the supplied quadrupole assembly fixture.
4. Assemble 16 single defocusing quadrupole segments (95D1733-2) into single quadrupole segment carrier (95C1736-2), as per Drawing 95C1750. Repeat to make the two single defocusing quadrupoles, using the supplied quadrupole assembly fixture.

MEASUREMENT AND SORTING OF MAGNET ASSEMBLIES

5. Make physical measurements of each assembly. Machine surfaces as needed to correspond to housing drawing, so they will fit into the housing properly. (Brobeck Corporation found that some assemblies, mostly quadrupoles, needed to be shaved).
6. Make magnetic measurements of each assembly.
7. Sort assemblies for final assembly in housing, based on the magnetic measurements (see Final Report, Appendix H, Volume II, pp. 26-28).

ASSEMBLE ACHROMAT TRIM COILS -- 95C1740-1 and -2

8. Wind conductor wire (item 1) into coils, using supplied fixtures.
9. Wrap with yellow mylar tape.

ASSEMBLE MANIFOLDS -- 95C1743

10. Assemble and test the pair of manifolds, as described.

ASSEMBLE ACHROMAT -- 95J1749

11. Make and install cooling circuits, as shown, and epoxy in place on outside of housing (95D1739).

12. Install the trim coils on the housing, and epoxy them in place.
13. Make trim coil interconnections as shown in schematic.
14. Place the bottom half of the housing in a horizontal position, and place the achromat beam tube (95C1752) parallel to it.
15. Slide the magnet assemblies onto the beam tube, taking special notice of their orientation (all "tops" must be "up," all orientation arrows aligned).
16. Pick up the beam tube with the magnet assemblies in place, and place it in the housing. Jiggle the assemblies to get each carrier sitting properly on the housing shelf.

NOTE: Not all parts on the assembly drawing were used in the prototype. The flange ring (item 11), retaining flange (item 13), retaining sleeve (item 14), barrier ring (item 15), and compression spring (item 18) were not used. In the final application, the achromat would be built as specified on the drawing.

17. Put the top half of the housing in place.
18. Install stainless steel clamp bands (item 24) as shown.
19. Install supply and return manifolds, with their associated plumbing. The achromat is now complete.

SET UP TEST ASSEMBLY -- 95D1781

20. Install adaptor spool (item 5) and vacuum transition flange (item 1), with associated hardware.
21. Cut upstream end of beam tube to specified dimensions.
22. Make vacuum weld joint on upstream end.
23. Now, go to the downstream end. Install bearing (item 6).
24. Install downstream mounting plate (item 20).
25. Install bolt ring (item 3).
26. Install diaphragm plate (item 4), noting orientation of polished surface.
27. Install adaptor plate (item 2)
28. Cut downstream end of beam tube to specified dimensions.

29. Make vacuum weld joint on downstream end. NOTE: Welder should use care in order not to warp the diaphragm plate.
30. To complete assembly for vacuum testing, see Note 2 on the referenced drawing.

TABLE 7-3. VERNIER PURCHASE ORDER LIST

The purchase orders for the vernier are included in Appendix C, Volume II.

P.O.	VENDOR	ITEM	ORDERED	REC'D	PRICE
80	Permaluster, Inc.	Alum. strip (1st order, not used)	02/20/85	03/07/85	\$628.60
130	Western Pipe & Eng'g	Manifold parts	05/17/85	06/28/85	\$1,325.00
131	Francis Plating	Conductor anodizing	05/21/85	06/07/85	\$1,223.91
132	McMaster-Carr	Epoxy	05/22/85	05/22/85	\$105.51
143	Diamond Tool	Parts fab.	06/03/85	08/15/85	\$4,403.00
155	Permaluster, Inc.	Alum. strip (2nd order, used)	06/14/85	06/30/85	\$632.97
172	McMaster-Carr	Insulating varnish (not used)	07/03/85	07/07/85	\$7.00
172	McMaster-Carr	Caustic soda	07/08/85	07/10/85	\$16.36
195	Permaluster, Inc.	Alum. strip (spare)	07/29/85	12/10/85	\$629.80
197	Francis Plating	Conductor anodizing	08/05/85	08/05/85	\$1,438.99
216	Western Pipe & Eng'g	Cooling coils fab.	09/04/85	09/04/85	\$166.00
222	Herrington-Olson	Photography	09/10/85	09/10/85	\$221.25
223	Danforth Screw & Bolt	Stainless steel hardware	09/11/85	09/13/85	\$16.70
224	Accurate Mfg.	Interface flange fab.	09/12/85	11/07/85	\$1,035.00
225	Accurate Mfg.	Mounting plate fab.	09/12/85	11/07/85	\$975.00
231	Long Filmalide	Photoprocessing	09/17/85	09/17/85	\$57.04
233	Bay Seal	O-rings	09/19/85	09/19/85	\$24.28
246	Omega Eng'g	Ceramic insulators (not used)	10/04/85	10/31/86	\$70.56
247	Danforth Screw & Bolt	Stainless steel hardware	10/04/85	10/08/85	\$189.39
252	Oakland Valve & Fitting	Swagelok unions	10/14/85	11/01/85	\$57.04
253	Caral Inc.	2-part tank fab.	10/15/85	11/18/85	\$2,928.75
254	Schrader Scientific	Instl. parts fab.	10/15/85	11/06/85	\$2,339.27
269	Oakland Valve & Fitting	Plumbing items (flex hose, etc.)	11/18/85	11/20/85	\$264.36
272	Omega Eng'g	Ceramic insulators	11/20/85	11/26/85	\$58.40
273	Covac Vacuum Services	Vac. leak checking	11/25/85	11/25/85	\$382.50

TABLE 7-4. VERNIER ASSEMBLY STEPS

ASSEMBLE Y COILS -- 95D1706

1. Wind aluminum strip on reel, and anodize as per specifications.
2. Inspect anodized strip, while winding it from the reel on which it was anodized onto a second reel (Brobeck Corporation used film reels, which each held 50'). As the anodized strip is being wound onto the second reel, put yellow mylar film tape on one side of the strip.
3. Assemble ten Y coils (2 sets, Y1-Y5) by bending strip into shape as per the referenced drawing, using fixture supplied to LLNL.
4. Wrap coils with overwrap of yellow mylar film tape.
5. Check electrically, for shorts.

ASSEMBLE X COILS - 95D1705

6. Repeat Y coil steps to build the ten X coils (2 sets, X1-X5).

ASSEMBLE COILS, COIL SPACERS, AND COOLING CIRCUITS -- 95D1710

7. Install the Y coil spacers. Epoxy the two opposite 95C1712-1 spacers to the horizontal center line of the coil spool (95D1707). Epoxy the two opposite 95C1712-2 spacers, etc., through 95C1712-6.
8. Install the Y coils in the appropriate slots. Wind all with mylar film tape, and set aside for epoxy to cure.
9. Repeat preceeding steps for the X spacers (95C1713-1 through -6) and X coils.
10. Install cooling coils (95C1709-1 supply, -2 return) on coil spool, in slots provided.
11. Spot weld electrical interconnections as per Detail B.
12. Check the system for electrical shorts and low resistance readings; check water path for stoppage or constriction.

ASSEMBLE COIL PACKAGE INTO TANK -- 95J1728

Upstream end

13. Assemble coil package and interface flange: assemble interface flange (item 3), lock nut (item 2), and coil package (item 1).
14. Lower above assembly into the 50 cm tank spool (item 36).

15. Clean O-rings, etc. and bolt the flange, O-ring, and tank together, using items 23, 42, and 44.
16. Install upstream pump-out spool (item 16-1), with specified hardware.
17. Install 6" lucite port cover (item 37).

Downstream end

18. Install the downstream mounting plate (item 4) using spring plungers (item 19) to center the coil spool in the opening.
19. Install the supply manifold assembly (item 7) and return manifold assembly (item 8) on the tank, using specified hardware.
20. Install pigtails -- supply connectors (item 11) and return connectors (item 12) -- to secure manifolds to coil assembly.
21. Install 2-port experimental tank (item 15), oriented as shown.
22. Install magnet power input flange (item 9), and magnet power terminal (item 14), and associated hardware.
23. Make coil connections, as shown, threading the ceramic insulators (item 31) onto the copper wire (item 30), making sure that the X coil leads are connected to the X coils, and the Y coil leads to the Y coils -- see Detail C.
24. Install cooling input flange assembly (items 10, 33, 39, 40, 41, 44).
25. Hook up cooling input flange assembly to return manifold (item 8), using flex hose (item 20).
26. Install downstream pump-out spool (item 35-2), with specified hardware.

8.0 ASSEMBLY DRAWINGS: ACHROMAT

TABLE 8.1 ACHROMAT DRAWING LIST

Dipole Assembly	95C1751
Quadrupole Assembly	95C1750
Trim Coil Assembly	95C1740
Water Manifold	95C1743
Achromat Assembly	95J1749
Interface & Vacuum Test Assembly	95D1781
Focusing Quad	95D1732
Defocusing Quad	95D1733
Dipole	95D1734
Segment Carrier - Quad	95C1736
Segment Carrier - Dipole	95C1737
Magnet Spacer	95B1738
Housing	95J1739
Manifold Fitting 1/2"	95B1741
Manifold Fitting 1/4"	95B1742
Flange Ring	95C1744
Adjusting Sleeve	95C1745
Retaining Flange	95B1746
Retaining Sleeve	95B1747
Barrier Ring	95B1748
Beam Tube	95C1752
Vacuum Transition Flange	95C1774
Adapter Plate	95C1775
Bolt Ring	95C1776
Diaphragm Plate	95B1777
Adapter Spool	95B1778
Bearing	95B1779
Alignment Bar	95B1780
Downstream Mounting Plate	95B1782
Spacer	95B1783
Stud	95B1784

A full set of as-built drawings for the achromat is included in Appendix D, Volume II. The six assembly drawings are also included in this section.

		<u>PAGE</u>
Dipole Assembly	95C1751	8-3
Quadrupole Assembly	95C1750	8-4
Trim Coil Assembly	95C1740	8-5
Water Manifold	95C1743	8-6
Achromat Assembly	95J1749	8-7
Interface & Vacuum Test Assembly	95D1781	8-8

- NOTE:
- 1. SCRIBE THE PART NO. AND AN ARROW IN THE BEAM DIRECTION ON EACH ASSEMBLY, SAND, SMOOTH.
 - 2. SCRIBE "TOP" ON THE TOP OF EACH ASSEMBLY, SAND SMOOTH.
 - 3. MAGNET MATERIAL IS FRAGILE. HANDLE WITH CARE.
 - 4. EACH DIPOLE ASSY MUST CONSIST OF PRE-SELECTED SEGMENTS, SEE BROBECK CORP SPECS. FOR SELECTION PROCEDURE.

QTY	PART NO.	DESCRIPTION	ITEM
10		SCREW, CAP, HEX 50C HD #4-40UNC-2B, .188	5
1	95C1737	SEGMENT CARRIER- DIPOLE	4
1	95D1734	DIPOLE	3
			2
			1
			ITEM

PARTS LIST		BROBECK MEMPHIS, CALIFORNIA 38114	
SEE P/L		BEAM DIRECTOR	
		ACHROMAT	
		DIPOLE ASSEMBLY	
		C 95C1751 A	
		SCALE NONE 135-28	
		PAGE 1 OF 1	

REVISIONS			
SYM	DESCRIPTION	BY	CHK
A	AS BUILT	W. J. J.

NOTE:

1. SCRIBE THE PART NO. & AN ARROW IN THE BEAM DIRECTION ON EACH ASSEMBLY, SAND SMOOTH.
2. SCRIBE "TOP" ON THE TOP OF EACH ASSEMBLY, SAND SMOOTH.

3. MAGNETIC MATERIAL IS FRAGILE. HANDLE CAREFULLY.
4. EACH QUAD. ASSY MUST CONSIST OF PRE-SELECTED SEGMENTS, SEE BROBECK CORR SPEC FOR SELECTION PROCEDURE.

12	12	12		SCREW, CAP. HEX SOCKET HD #4-40UNC-2AF-100 S5T	8
1			95C1736-2	SEGMENT CARRIER-QUADRUPOLE	6
1	1	1	95C1736-1	SEGMENT CARRIER-QUADRUPOLE	5
-			95D1733-2	DEFOCUSING QUAD SINGLE-ASSY	4
-			95D1733-1	DEFOCUSING QUAD DOUBLE-ASSY	3
-			95D1732	FOCUSING QUADRUPOLE ASSY	2
QTY	QTY	QTY	PART NO.	DESCRIPTION	ITEM
-3	-2	-1	DASH NO.	PARTS LIST	

95C1749 BEAM DIRECTOR QUADRUPOLE ASSEMBLY		SEE P/L DO NOT SCALE DRAWING		BROBECK BERKELEY, CALIFORNIA 947 BEAM DIRECTOR ALCHRONAT QUADRUPOLE ASSEMBLY SCALE NONE 95-26 SHEET 1 OF 1	
---	--	---------------------------------	--	---	--

ITEM ④ SCALE 2:1
FINISH 125 ALL OVER

SECTION A-A
TYP FOR ITEMS ① & ②
NOT TO SCALE

NOTE:

1. AFTER FORMING ITEM ③ DO THE FOLLOWING IN SEQUENCE:
 - a. SADDLE ITEMS ① & ② ON ITEM ③ AND WELD.
 - b. DRILL .406" HOLE THRU ITEM ① AND NEAR WALL OF ITEM ③.
 - c. DRILL .188" HOLE THRU ITEM ② AND NEAR WALL OF ITEM ③.
 - d. REMOVE CHIPS FROM INSIDE ITEM ③
 - e. WELD ITEM ④ IN PLACE.
 - f. HYDROTEST AT 300 PSIG FOR 10 MIN. - DO NOT EXCEED PRESSURE

QTY	PART NO.	DESCRIPTION	ITEM
4		BAR, .75" 304 SST	4
2	SEAMLESS	TUBING, .75" x .065 WALL 304 SST	3
2	95B1742	MANIFOLD FITTING - 1/2"	2
2	95B1741	MANIFOLD FITTING - 1/2"	1

PARTS LIST

BROBECK BERKELEY, CALIFORNIA 947	
BEAM DIRECTOR ACHROMAT WATER MANIFOLD (PAIR)	SCALE: 1:1 95-2B SHEET 1 OF 1

NOTE:

- ▶ GET TOGETHER WITH IT USING
- ▶ IT GOES TWO STEPS TO
- ▶ PLACE ONE UNDER ITEMS BEING
- ▶ INSTALL THEM GOES BETTER &
- ▶ POINTS ARE SIGNIFICANT ENOUGH
- ▶ SEE TABULATION FOR LOCATION
- ▶ ORIENT ITEMS TO THE
- ▶ SPOON AND TOP KIDNEY TOP
- ▶ CUT, ROASTY TUBING BULWARK
- ▶ COMPAKMENT SPRING IS APPROX
- ▶ EACH ELEMENT CONTAINS THE
- ▶ LOCATION WHEN THE

SECTION A-1

Section 8-B
4 (B)

FRAPS OF THIS IN PORTION OF LENGTH WHERE
 1. ①, ②, ③, ④, -1 ONLY.
 2. BETWEEN ADJACENT ITEMS ③, ④, ⑤, ⑥, -1 ONLY.
 3. ITEM 7 & 8 WITH TERMINALS ALL FACING
 SAME DIRECTION IN PLACE WITH ITEM 67.

LOCATION OF THESE ITEMS.
 ①, WITH PART AND ARROW ON FACE
 IS TOP.
 BETWEEN HANDLES, ITEM ①, AT ARROW.
 ASSOCIATED 956-1087-110-100, -1 ONLY.

THE PRE-SELECTED COMPONENTS AND
 THE ARROW IS ALSO PRE-SELECTED.
 SPEC. FOR THIS SELECTION CRITERIA.

ACCOMMODATION ELEMENT LOCATION TABLE		
ELEMENT	COORDINATES	WAVELENGTH
FOCUSING QUAD	22,000,000	8
DEFOCUSING QUAD	67,000,000	4
DEFOCUSING QUAD	211,000	8
SHIM		
DIPOLE	211,000	8

SECTION C-C

REVISION	
REV. NO.	DATE
956-1087-1	FUTURE USE
956-1087-2	ATA TEST

[illegible]

2

PLAN VIEW
SCALE: 1/2

(REMOVE) 2.88

2.19

SECTION A-A
SCALE: FULL

NOTES:

1. ALL WELDS TO BE VAC. TIGHT. TOTAL LEAK RATE TO BE LESS THAN 1×10^{-10} STD. ATM. CC/SEC AT MAX. BASE PRESS. OF 1×10^{-6} TORR WHEN MEASURED WITH A HE MASS SPECTROMETER.

2. FOR SPOOLS, COVER RATES & HDW. NOT SPECIFIED, SEE VERNIER STEERING MAGNET INSTALLATION DWS. 95T1728.

PAGE
3-3

			24
			23
4	95B1784	STUD	22
4	95B1783	SPACER	21
2	95B1782	DOWNSTREAM MFG. PLATE	20
24		NUT, PLAIN HEX $\frac{3}{8}$ "-16	SST 19
4		NUT, PLAIN HEX $\frac{1}{4}$ "-20	SST 18
48		WASHER, FLAT $\frac{3}{8}$ "	SST 17
16		WASHER, FLAT $\frac{1}{4}$ "	SST 16
			15
4		SCREW, HEX. NO. $\frac{3}{8}$ "-16 x 2 $\frac{1}{2}$ " LG.	SST 14
20		SCREW, HEX. NO. $\frac{3}{8}$ "-16 x 2 $\frac{1}{2}$ " LG.	SST 13
12		SCREW, HEX. NO. $\frac{1}{4}$ "-20 x $\frac{3}{4}$ " LG.	SST 12
36		SCREW, SKT. NO. 8-32 x $\frac{1}{2}$ " LG.	SST 11
1		O-RING PARKER 2-172 VITON	10
2		O-RING PARKER 5-569 VITON	9
1	95T1749-2	ACHROMAT	8
2	95B1780	ALIGNMENT BAR	7
1	95B1779	BEARING	6
1	95B1778	ADAPTER SPOOL	5
1	95B1777	DIAPHRAM PLATE	4
1	95C1776	BOLT RING	3
1	95C1775	ADAPTER PLATE	2
1	95C1774	VAC. TRANSITION FLANGE	1
QTY	PART NO.	DESCRIPTION	ITEM

LIST OF MATERIAL

BROBECK BERKELEY, CALIFORNIA 95D1781A	
95D1781A BEAM DIRECTOR ACHROMAT INTERFACE & VAC TEST ASSY	95D1781A

9.0 ASSEMBLY DRAWINGS: VERNIER

TABLE 9.1 VERNIER DRAWING LIST

Coil X ₁ - X ₅	95D1705
Coil Y ₁ - Y ₅	95D1706
Coil Assembly	95E1710
Installation	95J1728
Coil Spool	95D1707
Lock Nut	95C1708
Cooling Coil	95C1709
Y Coil Spacer	95C1712
X Coil Spacer	95C1713
Interface Flange	95E1714
Downstream Mounting Plate	95E1716
Manifold Clamp	95B1717
Manifold Fitting 1/2"	95B1718
Manifold Fitting 3/16"	95B1719
Supply Manifold	95D1720
Return Manifold	95D1721
Magnet Power Input Flange	95C1723
Magnet Cooling Input Flange	95C1724
Water Supply Connector	95B1725
Water Return Connector	95B1726
Spreader	95B1727
Magnet Power Terminal	95B1729
2-Port Exp. Tank	95D1769
Tank Spool (50 cm)	95D1770
Pump-out Spool	95D1771
Cover (6" Port)	95C1772
Cover (12" Port)	95C1773

A full set of as-built drawings for the vernier is included in Appendix E, Volume II. The four assembly drawings are also included in this section.

		<u>PAGE</u>
Coil X ₁ - X ₅	95D1705	9-3
Coil Y ₁ - Y ₅	95D1706	9-4
Coil Assembly	95E1710	9-5
Installation	95J1728	9-6

PLAN VIEW OF COIL PRIOR
TO FORMING OVER 280#
MANDREL

NOTES:

1. STRIP TO BE HARD BLACK AND GRADE .002 THICK, PRIOR TO WINDING.
2. PRIOR TO FINAL FORMING OF TERMINATIONS, COIL TO BE COATED TO DIMENSION SPECIFIC CHEMICAL METHOD AS APPROVED BY ENGINEERING DEPARTMENT.
3. GROUNDWRAP COIL WITH NYLON TAPES, USE 1/2 LAP METHOD, USE MINIMUM HOLD COIL SHAPE.
4. HI-POT COIL FOR ONE (1) MINUTE.
5. NOMINAL COIL DESIGN IS 17.14-2 FOR 2" BEND 3.45 MeV.

REVISIONS		
SYN	DESCRIPTION	BY
A	AS BUILT	OK

1.40
IS COIL R.

COIL STRIP PREP
(PRIOR TO WINDING)

TABULATION					
COIL DIM A	DIM B	NO. OF TURNS	PART NO.	REQD PER ASSY	DIM. W
X1	4.950	4.100	11	95D1705-1	2
X2	12.101	3.012	13	95D1705-2	2
X3	12.101	3.012	7	95D1705-3	2
X4	12.101	1.471	5	95D1705-4	2
X5	10.575	.728	3	95D1705-5	2

PAGE
9-3

ARI	INYLAR FILM TAPE .002THK YELLOW 2	1
ARI	STRIP .002X.150 AL 1100-0	1
QTY/PART NO.	DESCRIPTION	ITEM
PARTS LIST		
BROBECK BEVERLY CALIFORNIA U.S.A.		
BEAM DIRECTOR		
VERNIER STEERING MAGNET X COILS		
95D1705	D	95D1705 A

PLAN VIEW OF COIL PRIOR
TO FORMING OVER 2.254
MANDREL

NOTES:

1. STRIP TO BE HARD BLACK ANODIZED ELECTRICAL INSULATION GRADE .002 THICK, PRIOR TO WINDING COIL.
2. PRIOR TO FINAL FORMING OF TERMINATIONS. STRIP ANODIZED COATING TO DIMENSION SPECIFIED. USE MECHANICAL OR CHEMICAL METHOD AS APPROVED BY BROBECK CORPORATION ENGINEERING DEPARTMENT.
3. GROUNDWRAP COIL WITH MYLAR TAPE, ITEM 2, AFTER FORMING. USE 1/2 LAP METHOD. USE MINIMAL TAPE TENSION TO HOLD COIL SHAPE.
4. HI-POT COIL FOR ONE (1) MINUTE.
5. NOMINAL COIL DESIGN IS 20.830 AMPS TO GIVE 132 GAUSS FOR 2° BEND @ 45 M&V

NOTE:
1

[illegible][illegible]

NOTES:

10.0 PROJECT FUNDING

The beam director project was funded by the University of California under contract to the U.S. Department of Energy. The conceptual design study was performed for Lawrence Berkeley Laboratory, and the design, analysis, and building of prototype components for Lawrence Livermore National Laboratory.

<u>Date</u>	<u>Instrument</u>	<u>Amount</u>
6-2-83	Purchase Order 4522410: Conceptual design of an electron beam director.	\$ 47,763
9-19-86	Purchase Order 4522410, Change Order 1: Addition of planning for ATA tests.	6,185
10-1-83	Verbal authorization to proceed under Subcontract 2700700.	73,048
2-22-84	Subcontract 2700700, Amendment 11, Part E: Beam director components.	See above
2-29-86	Subcontract 4368008, Task II: Continuation of work initiated under Subcontract 2700700.	52,310
6-26-84	Subcontract 4368008, Amendment 2, Task II.C: Engineering design and detail for an electron beam window.	39,774
2-11-85	Verbal authorization to proceed with Subcontract 6551805: Beam director long lead material.	83,997
5-6-85	Subcontract 6551805 (formal).	See above
5-10-85	Subcontract 6551805, Amendment 1: Engineering support, fabrication, assembly, and bench test of vernier and achromat.	155,173
	TOTAL	<u>\$ 458,250</u>

Copies of these instruments are contained in Appendix A, Volume II.

Project costs by month, divided into "Labor" and "Other," are presented for the achromat and vernier (Subcontract 6551805) in Table 10-1. A man-hour summary for the achromat and vernier is presented in Table 10-2.

TABLE 10-1. PROJECT COSTS BY MONTH

	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
ACHROMAT												
Labor	2,479	2,400	5,322	12,086	4,000	12,091	8,137	7,951	12,854	3,429	8,745	79,494
Other	0	153	251	9,885	8,391	44,911	4,031	7,198	13,159	8,114	865	96,958
Total	2,479	2,553	5,573	21,971	12,391	57,002	12,168	15,149	26,013	11,543	9,610	176,452
VERNIER												
Labor	583	213	729	1,814	5,550	4,367	10,198	7,301	2,126	3,683	765	37,329
Other	0	899	0	462	1,077	7,080	6,393	947	-359	7,477	5,079	29,055
Total	583	1,112	729	2,276	6,627	11,447	16,591	8,248	1,767	11,160	5,844	66,384
ACH & VER												
Labor	3,062	2,613	6,051	13,900	9,550	16,458	18,335	15,252	14,980	7,112	9,510	116,823
Other	0	1,052	251	10,347	9,468	51,991	10,424	8,145	12,300	15,591	5,944	126,013
Total	3,062	3,665	6,302	24,247	19,018	68,449	28,759	23,397	27,280	22,703	15,454	242,836

TABLE 10-2. MAN-HOUR SUMMARY

<u>Labor Category</u>	<u>H O U R S</u>		
	<u>Achromat</u>	<u>Vernier</u>	<u>Total</u>
Senior Engineer	899	306	1,205
Engineering Designer	200	98	298
Engineering Technician	120	114	234
			<u>1,737</u>

11.0 REFERENCES AND BIBLIOGRAPHY

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