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**LAMPF Transition-Region
Mechanical Fabrication**

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LAMPF TRANSITION-REGION MECHANICAL FABRICATION

by

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ABSTRACT

The primary purpose of the new Transition Region (TR-II) is to optimize the phase matching of the H^+ and H^- beams during simultaneous transport. TR-II incorporates several design improvements that include larger aperture, a straight beam track, greater beam-path length adjustments, and utility lines integrated with the support system. The "close pack" density of magnets and beam-line hardware required innovative solutions to magnet design and mounting, vacuum manifolding, and utility routing. Critical magnet placement was accomplished using a new three-dimensional alignment system that does real-time vector calculations on a computer with input from two digital theodolites. All assembly and a large fraction of the mechanical fabrication were done by LAMPF personnel. The TR-II has been operational since September 1983 and routinely transports production beams up to 900- μ A current with no major problems.

I. INTRODUCTION

Design, construction, and initial installation of the 201-MHz drift-tube linac (DTL) and 805-MHz side-coupled linac (SCL) had started before the idea of simultaneous acceleration of H^+ and H^- beams was proposed.¹ The very limited

space between the DTL and SCL had been irreversibly established when design was started on the original Transition Region.

The purpose of the Transition Region is to match the output of the DTL to the input of the SCL. An additional path length of approximately 8 cm is required to establish a proper phase relationship between the two beams. This phase change allows both beams to be accelerated simultaneously through the SCL.

The original Transition Region shown in Fig. 1 had several limitations, which caused operational problems and limited independent matching of the H^+ and H^- beams. The new Transition Region (TR-II) was designed to eliminate these problems and incorporates the following major features: large aperture, straight track, additional diagnostics, space on long track for beam-path length adjustments, quadrupole magnets on all three tracks for independent matching, and utility lines integrated with the support structure for a neater installation. A schematic of TR-II is shown in Fig. 2.

This report covers the engineering design, construction, and installation of the TR-II.

II. CONCEPTUAL DESIGN

The basic configuration of TR-II shown in Fig. 2 was conceived by Andrew A. Biowman with analytical support provided by Oscar Sander.^{2,3}

Fig. 1.
Original Transition Region.

Fig. 2.
New TR-II.

Preliminary magnet design estimates indicated that the existing space between the DTL and SCL would not be adequate for TR-II. The required spacing was obtained by moving the complete 805-MHz module 5 downstream a distance of 0.46 m.

At this point the design became an iterative process to satisfy the major beam-transport conditions. These requirements were beam-matching criteria, with magnetic fields sufficiently low to minimize H^- stripping and still allow enough space for all of the required beam-line devices.

The two beams are deflected 20° by BM01 and restored to the accelerator axis by BM04. The short-path BM02 and BM03 magnets operate at fixed fields to provide 20° bend angles. The path length in the long track can be varied by adjusting bending magnets BM05, 06, 07, and 08, which have a combined bending angle of 40° . This is accomplished by powering all of the coil turns in BM01, 02, 03, and 04, and half of the turns in BM05, 06, 07, and 08, with one power supply at a constant current. The second power supply is variable and powers the other half of the turns in BM05, 06, 07, and 08. The ampere turns add in BM06 and 07 and buck in BM05 and 08 to provide a total variation in path length of approximately ± 2 cm. A schematic of power supply connections is shown in Fig. 3.

Fig. 3.
Schematic of power for bending magnets.

III. MECHANICAL DESIGN AND FABRICATION

An important goal for TR-II was to make it as uncluttered and serviceable as possible. Details of major systems are given in the following paragraphs, with a complete drawing list shown in Appendix A.

A. Scheduling

Separate programs were written using the ASA program and E-Z Pert Charts, to maintain project schedules for TR-II fabrication and installation activities. Initial input of time and manpower requirements was obtained from the person responsible for each task or set of tasks. A general meeting of those involved was held to review and consolidate the scheduling data, which were then put into the computer program to run the printouts and charts. A few meetings were held at appropriate times to update the complete schedule. A typical fabrication printout and installation bar chart are shown in Figs. 4 and 5.

Approximately 25 individuals were involved in managing separate specialized tasks. Task completions were required on time and in specific order. This scheduling activity proved to be most helpful and effective in the successful completion of the TR-II.

B. Magnet Design

The magnets dominate the space available in the new TR. Many design iterations were conducted to satisfy all of the constraints imposed by the beam transport, space available, and magnetic field limitations, in addition to providing magnets that were compatible with all of the other devices in the TR.

Small magnets dictate the use of high-current densities in the conductor and direct water cooling. High currents are required when using the relatively large hollow conductors that allow unrestricted flow, hence reducing the possibility of plugged water circuits.

PAGE NO
NEW TRANSITION REGION (TR-II) MP-8

PROJECT SCHEDULE REPORT

STATUS DATE FEB 23 82

SORT:

I	J	DUR	ACTIVITY DESCRIPTION	SORT CODE	ESD	LSD	EFD	LFO	FLT
TR1000	TR2000	1	TRANSITION REGION DESIGN FIXED		SEP 15 80ACT	SEP 15 80	SEP 15 80	SEP 15 80ACT	11
TR2000	SS1000	0			JUL 23 81	NOV 24 81	JUL 23 81	NOV 24 81	17
SS1000	SS1010	15	DESIGN SUPPORT STRUCTURE		MAY 4 81ACT	MAY 4 81	AUG 17 81	AUG 17 81ACT	17
SS1010	SS1020	7	PROCUREMENT		AUG 10 81ACT	AUG 10 81	SEP 23 81	SEP 23 81ACT	17
SS1020	SS1030	17	FABRICATION		JUL 22 81ACT	JUL 22 81	NOV 20 81	NOV 20 81ACT	12
SS1030	SS1040	8	ASSEMBLY & TEST		SEP 28 81ACT	SEP 28 81	NOV 24 81	NOV 24 81ACT	13
SS1040	SS1050	9	STAGE AT ETL		DEC 17 81ACT	DEC 17 81	FEB 22 82	FEB 22 82ACT	12
SS1050	AM1050	0			JUN 3 82	AUG 27 82	JUN 3 82	AUG 27 82	12
TR2000	AM1000	0			JUL 23 81	DEC 28 81	JUL 23 81	DEC 28 81	22
AM1000	AM1010	18	DESIGN ALIGNMENT MOUNTS		MAY 15 81ACT	MAY 15 81	SEP 21 81	SEP 21 81ACT	22
AM1010	AM1020	6	PROCUREMENT		NOV 18 81ACT	NOV 18 81	JAN 4 82	JAN 4 82ACT	17
AM1020	AM1030	17	FABRICATION		NOV 2 81MND	MAR 4 82	MAR 8 82	JUL 1 82	17
AM1030	AM1050	8	ASSEMBLY & TEST		MAR 1 82MND	JUL 2 82	APR 23 82	AUG 27 82	18
AM1050	AM1060	9	STAGE AT ETL		MAY 3 82MND	AUG 30 82	JUL 6 82	NOV 1 82	17
TR2000	QM1000	0			JUL 23 81	DEC 8 81	JUL 23 81	DEC 8 81	19
QM1000	QM1030	44	DESIGN QUAD MAGNETS		DCT 1 80ACT	OCT 1 80	SEP 24 81	APR 1 82MND	26
QM1030	QM1040	0			SEP 24 81	DEC 28 81	SEP 24 81	DEC 28 81	13
QM1000	QM1005	0			JUL 23 81	DEC 8 81	JUL 23 81	DEC 8 81	19
QM1005	QM1020	13	PROCURE MATERIAL		APR 6 81ACT	APR 6 81	JUL 7 81	JUL 7 81ACT	19
QM1020	QM1040	0			AUG 11 81	DEC 28 81	AUG 11 81	DEC 28 81	19
QM1000	QM1010	0			JUL 23 81	FEB 24 82	JUL 23 81	FEB 24 82	30
QM1010	QM1040	26	FABRICATE PROTOTYPE		JUN 1 81ACT	JUN 1 81	AUG 29 81	APR 1 82MND	30
QM1000	QM1015	0			JUL 23 81	FEB 24 82	JUL 23 81	FEB 24 82	30
QM1015	QM1040	26	FABRICATE TOOLING		JUN 1 81ACT	JUN 1 81	AUG 28 81	APR 1 82MND	30

Fig. 4.

Fabrication printout (sample page).

Fig. 5.
Installation bar chart.

The TR-II is made up of eight bending magnets, twelve quad magnets, and twelve steering magnets. There is but one design for each type of magnet, and their measured operating characteristics must be sufficiently alike to be interchangeable. This approach minimizes fabrication costs and permits a minimum spares inventory. The magnet gaps were determined from the clear aperture requirements, the vacuum beam-pipe deflection for the worst case for each type of magnet, and the clearance necessary for alignment. The computer program POISSON was used to establish the magnet iron and coil configurations necessary to achieve the required field quality, integral strength, and

effective length requirements. In view of the number of magnets and the demanding field quality, a prototype of each type was fabricated and measured prior to production.

Any of the magnets can be disassembled for maintenance or removed without disturbing the vacuum systems. The magnet cores were machined from C1006 steel. Conventional coil fabrication techniques were used: braided fiberglass sleeve insulation over hollow copper conductor, vacuum-cast in epoxy resin. All tooling, coil winding, and molds were fabricated by MP-8 personnel; the Plastics Section of MST-6 performed the coil casting. The MP-8 Alignment Section was involved in the design of all devices at their inception to ensure proper provisions for alignment.

Because space was at a premium, water-cooled electrical jumpers were used on all three types of magnets to simplify the installation. The jumpers carry the current from the main bus bars and, in the case of the quadrupole and steering magnets, also provide cooling water. The bending-magnet cooling requirement was great enough to require separate water manifolds.

To permit easy maintenance, the electrical and water connections were located for convenient access in the beam channel.

C. Bending Magnets

The bending magnets occupy more space in the new TR than do any of the other devices; hence their design and construction were the most demanding.

The maximum allowable field of 11.9 kG across a gap of 5.7 cm with an $\int B \cdot dl$ of 510 kG·cm was specified. In addition the field integral was to be uniform over the volume ± 1.5 -cm high by ± 8.9 -cm wide to within 0.1% in all magnets (including the spare) in order to be interchangeable. In the full "bucked" coil mode, the magnets must yield a near-zero field. POISSON was used to determine the magnet geometry necessary to achieve the field uniformity, integral strength, effective length, and the full-current minimum-field requirement.

A picture-frame configuration was selected because it has relatively uniform fields and long effective length for a given overall magnet length. To minimize the length, the top and bottom coil sections were limited to two layers each. The coil design had to produce sufficiently uniform fields in both adding and bucking modes. The coil had to be divided into two sections with equal numbers of turns. This constraint limited the coil design to a total number of turns $N = 8, 16, 24, 32, \dots$, etc. As shown in Fig. 6, several coil

Fig. 6.
Bending-magnet coil configurations evaluated.

configurations were evaluated; configuration "e" was selected because it satisfied POISSON, appealed intuitively, and was relatively easy to wind.

Based on this model, a prototype magnet was constructed and field measurements were performed with an NMR probe, rotating coil, flip coils, and Hall probes. The rotating coil measuring $(B_x^2 + B_y^2)^{1/2}$ was stepped in 6.4-mm increments through the magnet. These data were then integrated numerically to yield $\int B \cdot dl$. The flip coil was used to verify the data but was too large to permit "off axis" measurements. To achieve field uniformity, it was necessary to chamfer the pole ends. Figure 7 shows the results of chamfering for integral

Fig. 7.

Bending magnet pole trimming.

uniformity along the midplane axis. Based upon these data, it was decided to procure eight production magnets plus one spare. Most of the necessary tooling was complete after fabricating the prototype. The conductor was formed by MST-6, Metal Fabrication, by drawing our LAMPF standard 11.8-mm square by 7.0-mm i.d. copper conductor through a "Turks Head" to a 7.62 mm by 12.2 mm rectangular section. The bending magnets operate at ~ 2200 A with a current density of about 2910 A/cm^2 ; consequently each turn is a separately cooled circuit. Each six-turn, two-layer pancake was wound flat with bare conductor properly spaced, then the ends were formed 90° with special tooling. Each turn

then was insulated with braided glass sleeve and the turn-to-turn connections were made by brazing small copper spacers at specific crossover locations. The vertical straps on the side of the magnet permit connecting the magnets for one- or two-power supply operation. The design permits the magnet to be disassembled for installation of a beam pipe without disconnecting the cooling hoses.

All nine bending magnets were measured as accurately as possible at the 20° and 0° field levels. A detailed description of these measurements is given in a memorandum written by A. Browman.⁴ Table I shows the measurements of the effective length and $\int B \cdot dl$ through the central path when all magnets are powered at the nominal operating current. In the full bucking mode, a field integral of 1.5 kG·cm or 0.3% of the full adding mode of 516 kG·cm was measured. The magnets match each other to the 0.1% level, indicating good quality control during construction. Correcting individual magnets was not required to achieve this uniformity. Figure 8 shows more detailed measurements performed on one of the production bending magnets--in this case, measurements were made both vertically and horizontally from the central axis. All data in this figure were normalized by dividing $\int B \cdot dl$ by $\int B \cdot dl$ through the center of the magnet. The rectangular area in the figure with a height of $\pm 0.1\%$ and width of ± 90 mm shows the portion of the aperture that should lie within the 0.1% field uniformity requirement.

TABLE I
 l_{eff} FOR EACH MAGNET IN THE CENTER AT 2178 A (20° BEND)

<u>Magnet</u>	<u>$l_{\text{eff}}(\text{cm})$</u>	<u>$\int B \cdot dl(\text{kG} \cdot \text{cm})$</u>
TRBM1	45.18	515.90
TRBM2	45.15	515.60
TRBM3	45.17	515.87
TRBM4	45.14	515.47
TRBM5	45.17	515.81
TRBM6	45.19	516.02
TRBM7	45.17	515.71
TRBM8	45.18	515.94
SPARE	45.15	515.54
Average	45.17 ± 0.02 $(\pm 0.04\%)$	515.76 ± 0.19 $(\pm 0.04\%)$

Fig. 8.

TR BM01 $\int B \cdot dl$ vs position.

The effect of coil placement was not fully appreciated at the time of design. Consequently, the effective length was slightly longer than anticipated and there was some distortion of the magnet fields caused by the electrical terminations on one side of the magnet. The measured quality of the magnets was deemed sufficient for the application; however, further improvements can be made by additional chamfering in the future if necessary. Some of the steps involved in the construction of the magnets are shown in Figs. 9, 10, 11 and 12.

The characteristics of the bending magnets are shown in Table II.

Fig. 9.
Bending magnet coil winding.

Fig. 10.
Bending magnet coils.

Fig. 11.
Bending magnet wound coil and mold.

Fig. 12.
Bending magnet coil connections.

TABLE II
BENDING-MAGNET PARAMETERS

Aperture (gap by width)	57 by 217	(mm)
Pole length	388	(mm)
Field	11.418	(kG)
Effective length	451.7 ± 0.2	(mm)
$\int B \cdot dl$	515.76 ± 0.19	(kG·cm)
Turns	24	(Turns)
Current	2178	(A)
Current density in conductor	29.1	(A/mm ²)
Resistance	0.00996 ± 0.00003	(Ω)
Voltage	21.69	(V)
Power	47.24	(kW)
Water flow	1.5	(l/s)
Pressure drop	340	(kPa)
Temperature rise	8	(°C)
Weight	700	(kg)

D. Quadrupole Magnets

The magnetic requirements were determined by Oscar Sander using the beam transport code TRACE.³ Numerous tunes were evaluated, then narrowed down to a few that best met the criteria. Quadrupole strength $\int G \cdot dl$ for the strongest focusing quad plus a 50% safety factor was established as the design goal. The transport programs also established the clear aperture required through the beam pipe for the worst case. The pole diameter was fixed at 52 mm to clear the 51-mm diameter 304L stainless steel beam tube. Our magnet design was also required to match the existing TR power supplies, imposing a 1000-A maximum-current limit on the design. POISSON was used to establish the first-order iron core and coil configurations and the ampere-turn requirement. Several design iterations were performed to achieve the desired gradient of about 3 kG/cm with the 1000-A current criterion and the requirement that the coils be adequately cooled. Given the gradient and integral strength, the required effective magnetic length was established. The pole length was

determined empirically, based on data acquired from measurements performed on numerous quadrupoles by the magnet-measuring crew in the past.

Twelve quads were required for the new TR and it was decided to fabricate two spare units. Constructing and evaluating a prototype, in view of the number of magnets and the rather demanding field-quality requirements, was considered advisable. Most of the requirements were satisfied analytically, with the exception of the harmonic errors. Although the harmonic content was approximated by POISSON, the program is two-dimensional and cannot model end effects. This was the area where the full value of the prototype quad was realized.

The prototype quad was measured using two systems. One was a fast-rotating coil that could be positioned on the magnetic axis with its output measured using an HP Model 3582A wave analyzer. The coil assembly consisted of one coil much longer than the magnetic length of the quad and a short coil that permitted the measurement of the central and end fields. The second system was a stepped coil that measured the integrated harmonics and determined the error between the magnetic and mechanical centers. Our initial approach was to use the traditional pole end chamfers to reduce the typical $N=6$ harmonics. To speed up the process, different chamfers were cut on each end of the poles.

Table III shows the effects of the different end chamfers on the $N=6$ and $N=10$ harmonics. Harmonics determined by POISSON are also shown for comparison. It can be seen that although the $N=6$ effect was reduced by increasing the size of the chamfer, $N=10$ harmonics increased to an unacceptable value. The next approach used POISSON and the measured harmonic data to establish a new pole contour to minimize the undesirable harmonics. The result of this effort, shown in Table III, is labeled "modified poles." At this point, the integrated harmonic content was considered acceptable, and we proceeded with the fabrication of the production magnet. The production quads were exact replicas of the last version of the prototype.

The quad was designed to have a minimum overall size and to permit convenient assembly, installation, and maintenance. The core is split vertically through the centerline, allowing magnet removal without disturbing the vacuum system. The coils are wound with 7.34-mm square by 4.09-mm inside-diameter copper conductors with eight turns per pole. The coil is made up of two sections with two poles per section wound from a single length of conductor also split on the vertical centerline. This geometry permitted easy

TABLE III

QUADRUPOLE HARMONICS
FAST-ROTATING COIL

Chamfer (mm)	$\zeta N=6$	$\zeta N=10$	$\overline{\text{ENDS}} N=6$	$\overline{\text{ENDS}} N=10$	$fN=6$	$fN=10$
	$\%N=2$	$\%N=2$	$\%N=2$	$\%N=2$	$\%N=2$	$\%N=2$
0	0.91	0.84	10.54	0.17	5.1	1.68
1.27-2.54	0.91	0.77	8.96	0.66	-	-
3.81-5.08	0.99	0.98	5.97	1.68	3.68	2.57
6.35-7.62	1.03	0.96	3.91	1.71	2.74	2.70

ABOVE DATA NORMALIZED TO APERTURE RADIUS $\frac{V}{V_2} \left(\frac{R_p}{R_c} \right)^{N-2}$

0	1.64%	2.71%	18.9%	0.86%	5.1	1.68
1.27-2.54	1.64%	2.48%	16.1%	2.11%	-	-
3.81-5.08	1.78%	3.16%	10.69%	5.42%	3.68	2.57
6.35-7.62	1.85%	3.09%	7.01%	5.50%	2.74	2.70

HARMONICS FROM POISSON COMPARED WITH STEP-COIL DATA

	POISSON		STEP-COIL	
	$N=6$ $\%N=2$	$N=10$ $\%N=2$	$fN=6$ $\%N=2$	$fN=10$ $\%N=2$
Original Poles	-1.9	-2.69	5.1	1.68
Modified Poles	+3.6	-0.92	0.96	0.517

coil winding, formed two water circuits with no splices, and electrical connections that did not have conductors looping the beam. Some of the steps involved in the construction of the quad magnets are shown in Figs. 13, 14, 15 and 16.

All fourteen quads were measured extensively. A summary of these measurements is covered in detail in a memorandum written by A. Browman.⁵ All magnets had similarly shaped excitation curves, although the magnitude varied as much as 0.08% between different magnets. The magnetic and mechanical centers were coincident to within 0.08 mm. The two extremes in the normalized harmonic content measurements for the fourteen production magnets are shown in Table IV. The B_y was measured using a Hall probe at 2.54-cm offset from the centerline along the Z axis to determine the effective length. Near the center of the magnet the effective length is 12.00 ± 0.05 cm, and it increases by about 0.4 cm from the center of the quad to the pole radius. Figure 17 presents a plot of $\int G \cdot dl$ vs I. Dividing $\int G \cdot dl$ by l_{eff} gives the peak quadrupole gradient. The strengths ($\int G \cdot dl$) of all fourteen quad magnets were within 0.1% of each other. The typical parameters for the quadrupole magnets appear in Table V.

Fig. 13.
Quad coil winding (start).

Fig. 14.
Quad coil winding (finish).

Fig. 15.

Quad potted coil and mold.

Fig. 16.
Quadrupole magnet.

TABLE IV
MAXIMUM DEVIATION OF THE FOURTEEN QUAD
MAGNET HARMONIC MEASUREMENTS

<u>N</u>	<u>TRQM3 %N=2</u>	<u>TRQM8 %N=2</u>
2	100	100
3	0.032	0.069
4	0.072	0.085
5	0.11	0.087
6	1.2	0.96
7	0.10	0.034
8	0.083	0.044
9	0.051	0.015
10	0.56	0.55
14	1.2	1.2

TABLE V
QUADRUPOLE MAGNET PARAMETERS

Bore	52	(mm)
Gradient	2.74	(kG/cm)
$\int G \cdot dl$	32.74	(kG)
Pole length	100	(mm)
Effective length	120	(mm)
Amp•turn/pole	7200	(NI/pole)
Current	900	(A)
Current density	22.1	(A/mm ²)
Voltage	4.7	(V)
Power	4.23	(kW)
Water flow	120	(cm ³ /s)
Pressure drop	480	(kPa)
Temperature rise	8	(°C)
Weight	40	(kg)

E. Steering Magnets

Originally, combined vertical and horizontal steering magnets were considered for the new TR because of the space limitations. The transverse field uniformity and space constraints dictated the use of dipole magnets. At this point the approximate locations of the steering magnets were established. Several beam-transport tunes for the long and the short path were studied to determine the maximum $\int B \cdot dl$ required. The design bending strength was defined to be 50% greater than the maximum requirement. The magnet gap was the clear aperture, plus two times the beam pipe thickness, plus alignment clearance. With an $\int B \cdot dl \approx 30 \text{ kG} \cdot \text{cm}$ and a gap of 5.40 cm, the TR-II steering magnets are more in the nature of small water-cooled bending magnets than conventional steering magnets.

Again, POISSON was used to design the core and coil geometry. The pole length is small compared with the gap; consequently, most of the field is in the fringe. For this reason, and the fact that fourteen (twelve units installed plus two spares) steering magnets were to be constructed, it was necessary to perform extensive measurements on a prototype. All steering magnets are identical. Vertical and horizontal steering are achieved by rotating the magnet 90° .

Fig. 17.
Quad $\int G \cdot dl$ vs I.

The steering magnets are small "H" magnets with coils wound with 4.72-mm square by 3.18-mm inside-diameter hollow copper conductor. After construction of the prototype steering magnet, very little work was required to prepare the winding form and casting mold for production. Some of the construction phases are shown in Figs. 18 and 19.

Typical characteristics of the new TR-II steering magnets are shown in Table VI.

Fig. 18.
Steering-magnet coil winding.

Fig. 19.
Steering magnet.

F. TR-II Magnet Alignment Mounts

The beam-transport design for TR-II requires a very large number of components to be positioned in a confined space (shown schematically in Fig. 2) and in the beam channel (Fig. 20). The traditional approach of individual adjustable mounts for each component was not practical for this close-packed

condition. A mounting design was originated which grouped the components on a common base. This saddle base was machined to hold quads, steering magnets, and beam boxes in precise ± 0.05 -mm fixed alignment relative to each other. Magnets and beam boxes were positioned on the saddles to this accuracy using shoulder screws. The complete saddle, shown in Fig. 21, was mounted so that an entire group of components could be aligned to beam line. The bending magnets were mounted on standard three-point supports. A unique feature of the bender support system and magnet design, shown also in Fig. 21, allows the magnets to be removed without breaking the vacuum envelope (accomplished by removing the top half of the magnet and lowering the bottom half until the beam pipe is clear of iron and coils). This section is then moved transversely until it is out from under the beam pipe. The quad and steering magnets can also be disassembled for removal.

TABLE VI
STEERING-MAGNET PARAMETERS

Gap	54	(mm)
Width	97	(mm)
Field	2.9	(kG)
$\int B \cdot dL$	27	(kG·cm)
Pole length	44.5	(mm)
Effective length	85	(mm)
Amp·turns	15,000	(NI)
Current	250	(A)
Current density	18.6	A/mm ²
Voltage	7.5	(V)
Power	1.9	(kW)
Water flow	44	(cm ³ /s)
Pressure drop	550	(kPa)
Temperature rise	10	(°C)
Weight	9	(kg)

Fig. 20.
TR-II "dense pack" beam transports.

G. TR-II Alignment

Initial tolerances requested for the location of TR-II components were very tight (on the order of ± 0.05 mm). A quick analysis indicated that if all components were machined to the smallest practical limit, an overall best effort would be in the (± 0.08 mm) range for component location. This error is the accumulation of tolerances for the magnet tooling hole location (± 0.03 mm), fixture fabrication (± 0.01 mm) and optical tooling limits of 6.1 m/200,000

Fig. 21.
Magnet alignment mounts.

(± 0.03 mm). This type of precision ruled out the normal method of TR alignment using portable instrument stands for alignment scopes and hand-held tooling scales referenced to an offset line. Two completely different systems were studied as solutions to this critical alignment task.

Our first proposal was to install a permanent two-bar tooling dock in the Transition Region. This would require a horizontal x-bar mounted above module 5 and a z-bar located along the south wall of the beam channel. These tooling bars would function as a standard tooling dock and give optimum results due to rigid instrument-mounting and self-checking features of a tooling dock. This

system would require dedicated equipment to stay in the beam channel and it would also take up valuable space.

The other system considered was a three-dimensional measuring system based on two digital theodolites interfacing with a desktop computer - this new technology was available from two companies. The two systems were demonstrated at Los Alamos and had hands on evaluation by our alignment technicians. It was soon evident that the computer-aided alignment systems were capable of ± 0.08 - 0.13 -mm precision in three-dimensional setups and had the features to be very versatile. This system's performance was sufficiently impressive that a decision was made to purchase one for the TR-II alignment and for other projects in the future.

The alignment system, a K&E "AIMS" shown in use at TR-II in Fig. 22, will be discussed in detail later in the report. Some development was necessary to make targets that were best suited for three-dimensional measuring; a cone-shaped target was chosen as the best for all-direction viewing. Three members of the alignment section were sent to the vendor's plant for training in the system's use and applications. The alignment crew also practiced using the system on magnets at the TR-II staging area in the Equipment Test Lab (ETL).

All TR-II beam line components requiring optical alignment were processed through the ETL tooling dock. This procedure involved precise mechanical measurements and the mounting of alignment target pads on the magnets. Quadrupole magnets, steering magnets, and beam boxes were checked for relative alignment when mounted in their common cradle.

Initial alignment of the magnets on their alignment mounts was done at the ETL staging area. Alignment of actual beam line parts on the support structure was done to $\sim \pm 1.5$ mm. Rough alignment allowed precise placement of water and power leads to the magnets, which helped to assure that parts would fit during installation in the beam channel.

The Analytical Industrial Measuring System (AIMS) is a new alignment system developed by the Keuffel and Esser Co. It consists of two digital electronic theodolites, a controller/computer, a printer, and a cart assembly (see Fig. 22). The theodolites have LED digital readout with angular resolution of 9×10^{-4} degree. The controller is a microcomputer with dual diskette drives, video display screen, and keyboard. The system's software package has the capability of doing several different measurement routines (see Appendix B). Angles from the theodolites are electronically entered into the computer, which

Fig. 22.

Keuffel and Esser Analytical Industrial Measuring System, (AIMS).

then performs the three-dimensional vector arithmetic and prints the output. A typical working printout is shown in Fig. 23. Data printed for each target station are the following:

1. target number and comment if desired;
2. azimuth and elevation angles for each theodolite; and
3. triangle apex angle, formed by theodolites and target; this can be used as a figure of merit in determining measurement accuracy.
4. XYZ coordinates and error from theoretical coordinates.

THURS. 5/12/83 1:00 PM

RESTART AFTER LUNCH, COMPLETE SET OF DATA FOLLOWS

ANALYTICAL INDUSTRIAL METROLOGY SYSTEM,
WITH K&E DIGITAL THEODOLITES...JOB 1

DIRECT DIGITAL THEODOLITE Nbr 1 AZIMUTH= 0.0000 ELEVATION= 83.4440 DEGREES
DIRECT DIGITAL THEODOLITE Nbr 2 AZIMUTH= 0.0000 ELEVATION= 82.9032 DEGREES
ABOVE WERE AZIMUTH ZERO REF READINGS

AUTOMATIC MODE
THEODOLITE OBLIQUE SEPARATION= 157.535 SYSTEM RESTART WITH UNDISTURBED SETUP

101 BM-1 UP

DIRECT DIGITAL THEODOLITE Nbr 1 AZIMUTH=329.9904 ELEVATION=106.6145 DEGREES
DIRECT DIGITAL THEODOLITE Nbr 2 AZIMUTH=320.4549 ELEVATION= 97.3581 DEGREES
MEASUREMENT TRIANGLES APEX = 58.143 DEGS.
UCx=-.0000 UCy=-.0002 UCz=-.0007 INCH, ARE COMPONENTS IN XYZ DIRECTIONS.
79 X = 14.3904 INCHES. Y = -0.0050 INCHES. Z = 10.0784 FOR TARGET 101
XERR= +0.0044 INCH. YERR= -0.0050 INCH. ZERR= +0.2714 FROM NOMINAL
UNCERTAINTY ANGLE = 0.0002 DEGREES, EQUAL TO -0.007 INCH + OR - FROM MEAN.
L= 83.173 AND R= 184.706 RANGES FROM THEODOLITES TO TARGET.

HAVE RE-ZEROED COORDINATE SYSTEM

400 TARGET

DIRECT DIGITAL THEODOLITE NBR 1 AZIMUTH=316.0935 ELEVATION= 97.0336 DEGREES
DIRECT DIGITAL THEODOLITE NBR 2 AZIMUTH=317.9781 ELEVATION= 92.9130 DEGREES
MEASUREMENT TRIANGLES APEX = 47.439 DEGS.
UCx=0.0000 UCy=0.0002 UCz=0.0014 INCH, ARE COMPONENTS IN XYZ DIRECTIONS.
80 X = -27.8976 INCHES. Y = 79.4326 INCHES. Z = -10.3886 FOR TARGET 400
XERR=-21.9666 INCH. YERR= +79.4326 INCH. ZERR= -33.8596 FROM NOMINAL
UNCERTAINTY ANGLE = 0.0004 DEGREES, EQUAL TO 0.0014 INCH + OR - FROM MEAN.
L= 84.828 AND R= 201.990 RANGES FROM THEODOLITES TO TARGET.

Fig. 23.

AIMS real-time printout of alignment data.

5. uncertainty angle -- mis-aim error of lines of sight and the equivalent distance in inches.

6. distance between last two targets.

A TR-II coordinate system reference was established by target #400 on the 201-MHz tank and target #500 on the 805-MHz module 5, as shown in Figs. 24 and 25. These two monuments were the master targets used to position all components in the TR-II.

Fig. 24.
Target station #400 201-MHz tank 4.

The procedures for using the AIMS are detailed in the following steps:

1. Electronically level each theodolite.
2. Establish a common baseline between the two instruments by pointing at each other in the direct and reverse sighting modes. This is recorded in the computer.
3. Set zero reference azimuth angles for each instrument by sighting on a common target and recording.
4. Set system scaling factor by sighting and recording two target positions on a known gauge bar, as shown in Fig. 20.
5. Sight on master targets #400 and #500 and transfer coordinate system origin from theodolite #1 to the master targets.

Fig. 25.
Target station #500 805-MHz module 5.

6. Component targets can then be sighted for alignment measurements. A theoretical X, Y, and Z coordinate position for each target on every magnet was entered into the computer. As the measured data are entered, they are automatically compared to the theoretical position and the difference is printed out as X, Y, and Z errors. A recapitulation of coordinate data with errors is shown in Appendix C.

The AIMS was not used to set elevation, as evidenced by the large Z errors shown in Fig. 23 and Appendix C. A Zeiss level, shown in Fig. 26, was used with tooling scales to make direct elevation readings from the magnet-alignment pads. The AIMS can make exact elevation measurements, but the target elevation must be referenced exactly to its seating shoulder in the tooling hole. For a clear line of sight, it was occasionally necessary to move a target vertically, thus destroying the target's elevation reference. The optical level can accommodate offsets without extra measurements or calibrations. The AIMS X, Y, and Z axes identification is equal to the X, Z, and Y axes on the accelerator.

Fig. 26.
TR-II elevation reading with a Zeiss level.

The complete TR-II alignment process was performed twice in the beam channel. The preliminary alignment was done to $\pm 0.25\text{-mm} - 0.38\text{-mm}$ prior to the installation of water, electrical, and vacuum services. Final alignment to $\pm 0.12\text{-mm}$ or better was done after all installation was complete, except for beam box actuators.

H. TR-II Support Structure

The TR-II support structure was designed to satisfy a variety of requirements. The primary conditions were that (1) structural design be done to minimize deflection, (2) utility lines be integrated with structure members where possible, (3) underside of support be clear for vacuum pump mounting and personnel access, (4) rigidity of structure be adequate to allow movement of

loaded support assembly without damage to components or utility lines, (5) standard structural shapes with welded joints be used for economy and to provide a rigid frame, and (6) one frame rail have a removable section to allow for future bucket rotator installation.

The basic structure was fabricated from wide-flange steel beams and square structural tubing, as shown in Fig. 27. Lateral braces are positioned at 45° to provide maximum torsional stiffness. Heavy components are located over major structure members as shown by base plate locations in Fig. 28. Calculations indicate that this structure will have a maximum deflection of ~ 0.8 mm under a full load of 9000 kg.

The structure has notches and holes cut at proper locations, as shown in Fig. 27, to allow close packed routing of utility lines. These include a 50-mm square copper bus for magnet power, cooling-water manifolds, and copper lines for bus-to-magnet jumper leads.

I. TR-II Vacuum System

The TR-II vacuum system has been designed as an integrated system in order to correct some previous problems of poor pump-down time and maintenance access. The prime design considerations were fast pump-down time and maintenance of high conductance in the vacuum lines. These requirements are especially important in the TR because fast turnaround times are necessary for repairs to minimize downtime.

A layout of the vacuum system is shown in Fig. 29. The 51-mm-diameter beam pipes follow three beam paths through the TR-II. Triangular vacuum chambers are positioned in BM-01 and -04. A 153-mm-diameter manifold runs lengthwise in the support structure connecting to the beam pipes, as shown in Fig. 29. This pipe has drop connections for three 500-l/s ion pumps, one cryopump, two roughing ports, and one auxiliary port.

The close-packed spacing of the magnets and beam boxes did not allow room for the use of LAMPF standard flanges at most joints. Special joints and vacuum envelopes were designed so that reliable seals could be made in extremely restricted space. The joints between steering magnets and beam boxes utilized a split-ring flange with a Con-O-Ring type seal. The sealing disc is thin enough to allow limited bellows-like deflections. Bolt clearance is so tight that hex drive rods were assembled in place in the mounting cradles to allow removal of socket head screws.

Fig. 27.
TR-II support frame.

Limited spacing between BM-05, -06, -07, and -08 and a beam box between BM-06 and -07 dictated the need for a continuous beam envelope without joints in this area. The resulting design, shown in Fig. 30, was nicknamed the "Albatross," for obvious reasons. This chamber was fabricated from 2.4-mm-thick stainless steel with the machined center section functioning as a beam box.

Fig. 28.

TR-II component base plates.

The BM-01 vacuum chamber also functions as a low-energy beam absorber. The absorber was made by adding Poco graphite and water cooling to the chamber wall exposed to the proton beam. The graphite was covered with 0.05-mm titanium foil to hold it in place if breakage occurs.

Fig. 29.
TR-II vacuum system.

Space limitations required custom-built vacuum isolation valves at each end of the TR-II, so the valves were designed integrally with the end beam boxes as shown in Fig. 31, increasing their overall length by only 19 mm. In the open position, the valve gate is offset approximately 2 mm from the sealing surface. When the valve is closed, the sealing force is provided by an air cylinder and the wedge action of mating inclined planes. The entire mounting system is flexible enough to permit the gate to move 2 mm sideways and remain parallel to the sealing surface.

Parameters of the TR-II vacuum system are given in Appendix D.

J. TR-II Electric Power System

The TR-II power system was designed jointly by MP-11 (power supplies) and MP-8 (bus bars and distribution). Power supply specifications are listed in Appendix E. Considerable attention was paid in routing magnet power to minimize

Fig. 30.

TR-II vacuum and beam-line components.

stray fields. Magnet power leads and bus bars were designed so that large currents (± 3000 A) that induce stray fields in the area of the conductor would cancel each other. A section of the power distribution system is shown in Fig. 32, illustrating how the hardware was integrated with the support structure and routed to make a neat and compact, yet accessible, assembly. The

Fig. 31.

TR-II custom-built isolation valve.

water-cooled jumper leads shown in Fig. 33 were positioned after preliminary alignment had been done. This procedure allowed each lead to be made to the exact required length, not with a long pigtail as is often the case for magnet hookup leads.

Figure 3 shows the power schematic for the TR-II bending magnets.

K. TR-II Cooling-Water System

The TR-II cooling system was designed to remove 1.5 MW of heat, twice the cooling load for the original TR. This increase is primarily the result of the use of more magnets, larger bend angles, and larger apertures. The bucking and

Fig. 32.

TR-II magnet power distribution.

adding fields to control the H^- path length also require considerably more power than does a normal shunt system.

The sector "A" (A02) water system that cooled the original TR runs close to its maximum capacity. To cool the TR-II it was decided to use the 805-MHz (B02) system because it has extra capacity available. This choice will allow high-power operation during the summer.

All components in the TR-II were designed to operate with a low (500-kPa) pressure drop cooling water requirement. This selection allowed the use of a low head, high capacity, single stage, centrifugal pump. Since accurate temperature control of the cooling water is not required, an air-operated temperature control system that maintains return water at $\sim 29^\circ\text{C}$ was used. This system was used on the original TR. It should continue to provide adequate control. Figure 34 is a schematic of the TR-II cooling-water system. The primary protection for all magnets in TR-II is interlocked with pump power. The

Fig. 33.

TR-II magnet water-cooled power leads.

secondary system utilizes thermal switches that trip the power supplies if high temperatures at the magnets are detected. The flow switch on each component's return line provides an interlock signal to prevent powering that component without cooling-water flow. The flow interlocks are a back-up safety system. This arrangement is similar to the original TR safety circuit that has proven to be effective in protecting equipment from cooling-system failures. TR-II cooling-system equipment is listed in Appendix F.

IV. TR-II STAGING AND INSTALLATION

It was decided early in project planning that preinstallation staging of the complete TR-II would be required. This decision was necessary because of the extreme density of components and the existence of a fixed time window for installation of TR-II in the beam channel. The installation schedule could not allow any time for rework.

The complete TR-II was assembled at the Equipment Test Laboratory (ETL), as shown in Fig. 35. This staging allowed the magnets, bus bar, cooling manifolds, and vacuum pipe to be custom-fitted to the support structure. A mockup of the wireways made it possible to order made-up lengths of water-cooled power cable. The move from ETL to the beam channel was made by removing the magnets and loading the support structure on a lowboy trailer for transporting. The water manifolds, heavy power bus, and part of the magnet mounts remained with the support.

Removal of the old TR to the stage shown in Fig. 36 and installation of the new TR-II to the point shown in Fig. 37 were accomplished in ten working days.

Adequate planning, good coordination, and dedicated people made this move a smooth and rapid operation. Once the magnets were in position, the installation of water, power, vacuum, beam diagnostics, and control wiring was started.

Fig. 34.
TR-II cooling water schematic.

Fig. 35.
TR-II staged at ETL Building.

V. CONCLUSION

After completion of the new Transition Region, the power supplies, controls, and interlocks were tested in preparation for the 5 July 1983 turn on, which went quite well. Beam tuning was performed and production beam was delivered to the experimental area on 1 August 1983. Beams have been transported through all three paths, with H^+ and H^- beams delivered through the short and long tracks simultaneously. H^+ beam currents of 900 μA have been successfully transported for production beams. After several months of operation, all devices are performing as desired and the alignment seems to be sufficient. At this time (April 1984) no changes in design have been proposed.

Fig. 36.
Space for the TR-II in the beam channel.

Fig. 37.
TR-II installed in beam channel.

VI. ACKNOWLEDGEMENTS

The successful turn on of TR-II was the culmination of effort by many dedicated people. The overall project responsibility was managed by MP-8 with MP-11 support in the areas of power supplies, beam diagnostics, and vacuum. Special thanks are due Arlene Lopez for compiling and production of this paper. Those people who had major involvement with this project, and their areas of contribution are listed below:

Chester R. Smith	Drafting
Michael J. Burns	Drafting
Ralph K. Lopez	Drafting
Steven F. Archuletta	Magnet Measurement
Michael G. Mays	Magnet Measurement
Maynard R. Roberts	Magnet Measurement
Patrick A. McClellan	Magnet Fabrication
David J. Honaberger	Magnet Fabrication
Edward M. Perez	Magnet Fabrication
Gilbert Suazo	Cable Trays, Safety Fence, General Fabrication
Clifford Gladwell	General Fabrication
Dorwin R. Justice	General Fabrication
Gilbert J. Gonzales	General Fabrication
Tomas O. Sanchez	Vacuum Component Welding
Edward R. Weiler	Installation & Alignment
Justo F. Cordova	Installation & Alignment
Edward J. Schneider	Power Supplies
Richard Tregellas	Diagnostics
Louis Morrison	Vacuum Installation
Bobby Poe & Vacuum Crew	Vacuum Installation
Edwin Eaton & MST Plastics Section	Coil Potting

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1. D. A. Swenson, "The Transition Region," MP-Division internal report MP-3-75 (February 1969).
2. O. R. Sander, "LAMPF Transition Region," Los Alamos National Laboratory report LA-9315-MS (June 1982).
3. O. R. Sander, A. A. Browman, and E. D. Bush, Jr., "Redesign of the LAMPF Transition Region," Particle Accelerator Conference, 1981, Proc., IN-IEEE Trans. Nucl. Sci., V. NS-28, p. 2914-5 (1981).

4. A. A. Browman, "TR Bending Magnet Description," Los Alamos National Laboratory memo (August 1983).
5. A. A. Browman, "TR II Quadrupole Magnets," Los Alamos National Laboratory memo (April 1983).

APPENDIX A

TR-II DRAWING LIST

60Y-124450	TR-II Magnetic Effective Lengths
60Y-124451	TR-II Envelope Drawing
60Y-124452	TR-II Bending Magnet Iron
60Y-124453	TR-II Coordinate System
60Y-124454	TR-II Steering Magnet
60Y-124455	TR-II Beam Box-09 & Vacuum Chamber for BM-05, BM-06, BM-07 & BM-08
60Y-124456	TR-II Installation Drawing
60Y-124457	TR - Model II Prototype QM Iron
60Y-124458	TR-II Beam Box 2-80, 10-12
60Y-124459	TR-II Support Structure
60Y-124460	TR-II Alignment Mount - BM
60Y-124461	TR-II Alignment Mounts BMs, SMs, & QMs
60Y-124462	TR-II Potting Form Quad Magnet Coil
60Y-124463	TR-II Cradle Assembly Group 1 & 4
60Y-124464	TR-II Cradle Assembly Group 2 & 3
60Y-124465	TR-II Cradle Assembly Group 5-6 & 7-8
60Y-124466	TR-II Cradle Assembly Group 9-10 & 11-12
60Y-124467	TR-II Beam Box-1 & Slow Valve Assembly
60Y-124468	TR-II Electrical & Plumbing
60Y-124469	TR-II Vacuum System
60Y-124470	TR-II - BM-01 & BM-04 Alignment Mount Filler Plate
60Y-124471	TR-II Water System Valve Mode Indicator
60Y-124472	TR-II Gaussmeter (Modified)
60Y-124473	TR-II Vacuum Chamber 3M-04
60Y-124474	TR-II Vacuum Chamber BM-02 & BM-03
60Y-124475	TR-II Inspection Fixture BM-02 through BM-12
60Y-124476	TR-II Support & Alignment Mount for BM-01
60Y-124477	TR-II Rotating Coil Quadrupole Magnets
60Y-124478	TR-II Retaining Ring for BB-01
60Y-124479	TR-II Q.M. Feedthru
60Y-124480	Pier Assembly, 805 MHz, Module 5 Upstream
60Y-124481	TR-II Vacuum Manifold Center Section
60Y-124482	TR-II Vacuum Manifold
60Y-124483	TR-II Support and Alignment Stand for BB-13
60Y-124484	TR-II Vacuum Chamber BM-01
60Y-124485	Potting Form TR-II BM Coils
60Y-124486	TR-II Steering Magnet Beam Absorber

60Y-124487	TR-II Vacuum Tube Support
60Y-124488	TR-II Alignment Fixture for Quad Magnets
60Y-124489	TR-II Alignment Fixture for Quad Magnets
60Y-124490	TR-II Short Track Energy Absorber
60Y-124491	TR-II Long Track Energy Absorber
60Y-124492	TR-II Bending Magnet-Water & Elec. Jumper Blocks
60Y-124493	TR-II Vacuum Manifold Center Support
60Y-124494	TR-II Beam Box Flange
60Y-124495	TR-II Manifold to Beam Pipe Adaptor
60Y-124496	TR-II Beam Pipe
60Y-124497	TR-II Manifold to Beam Pipe Adaptor
60Y-124498	TR-II Vacuum Pipe Support
60Y-124499	TR-II Gaussmeter Mod. II

APPENDIX B

"AIMS" APPLICATION PROGRAMS

Application Programs*

1. Manual Measure Normal routine outputs, coordinates distance between points & point ID. 2. Auto-Measure Same as Manual but defaults name to event counter for rapid measuring. 3. Average Multi-Readings Used when target is difficult to see, averages repeated readings. 4. Laser-Mirror Outputs azimuth and elevation angles of object surface. With the aid of small laser computes direction of the normal to a mirror surface.	5. Paraboloids For antenna manufacture and QA. Facilitates calibration of parabolic surface. 6. Transform Changes coordinate system to new orientation. 7. Set-Point Used to place object to target at predetermined coordinate position. 8. Compute Length Outputs length between any two previously measured points. 9. Find Circle Center Given three points, calculates coordinates of circle center.	10. Sphere Size or deviation of Spheroid. 11. Cylinder Size of deviation of Cylinder (tank). 12. Out of Round Deviation of circle points. 13. Hidden Point To compute location of point which cannot be seen by theodolites. 14. Delta X, Y, Z Computes difference in X, Y, Z between two successively measured points.

*Subject to change or modification without notice.

APPENDIX C

RECAPITULATION OF DATA WITH ERRORS GIVEN NOTE: Z DATA ARE INVALID

FOLLOWING IS A RECAPITULATION FOR NUMBERED TARGETS OF THE BLUEPRINT NOMINAL X, Y DIMENSIONS, AND THE ERRORS FROM THOSE NOMINALS. THE LAST COLUMN, UNCERTAINTY ANGLE IN DECIMAL DEGREES, REFLECTS THE QUALITY OF THE POINT TO EACH TARGET. DELTA IS THE DISTANCE TO THE PREVIOUS TARGET, OR ELSE THE DEVIATION FROM A FITTED MATHEMATICAL SHAPE.

EVENT	X	X error	Y	Y error	Z	Z error	UNC ANG	Unc INCH	DELTA	IDENTIFYING NUMBER and/or COMMENTS
80	-27.8976	-21.9666	79.4326	+79.4326	-10.3886	-33.8596	0.0004	0.0014		400 TARGET
81	190.5609	-21.9751	78.4842	+78.4842	-10.3887	-33.8597	0.0004	0.0016	218.461	500 TARGET
82	-5.9310		0.0000		23.4710		0.0000	0.0000		RESET
83	212.5296		-0.0000		23.4709		0.0000	0.0000		RESET
84	14.3864	+0.0004	-0.0033	-0.0033	10.0789	+0.2719	0.0004	-0.0014		101 BM-1 U
86	-5.9310	-0.0000	0.0000	+0.0000	23.4710	-0.0000	0.0004	0.0014	36.8391	400 TARGET
87	28.3833	-0.0027	-0.0017	-0.0017	10.0705	-0.2636	0.0003	-0.0008	36.838	102 BM-1 D
88	36.7412	-0.0028	5.4873	-0.0037	6.6865	+2.0645	0.0010	-0.0028	10.5563	124 SM-1
89	42.9747	-0.0053	7.7617	+0.0007	7.5003	+1.6883	0.0011	-0.0032	6.6852	125 QM-1
92	66.6460	-0.0030	13.7250	-0.0030	7.1829	+0.2509	0.0007	-0.0019		105 BM-2 D
93	52.6444	-0.0036	13.7241	-0.0039	7.1829	+0.2509	0.0003	-0.0008	14.0016	104 BM-2 U
100	72.6826	+0.0016	13.7269	-0.0001	6.6773	-0.0077	0.0002	-0.0005	+ .0063	126 SM-2
101	80.2473	+0.0033	13.7286	+0.0016	7.5056	+1.6936	0.0012	-0.0030	7.6099	127 QM-2
104	122.9273	-0.0107	13.7233	-0.0037	7.4980	+1.6860	0.0033			128 QM-3
105	130.4991	-0.0009	13.7255	-0.0015	6.6983	+0.0133	0.0003	0.0008	7.6139	129 QM-3
106	136.5304	-0.0036	13.7241	-0.0039	7.1860	+0.2560	0.0002	0.0005	6.051	107 BM-3 U
107	150.5319	-0.0021	13.7287	+0.0007	7.1843	+0.2543	0.0006	-0.0017	14.0015	108 BM-3 D
109	160.2041	+0.0021	7.7635	+0.0025	7.4935	+1.6815	0.0006	-0.0016	+ .0081	130 QM-4
110	166.4335	-0.0035	5.4883	-0.0027	6.6958	+2.0738	0.0007	-0.0019	6.6797	131 SM-4
111	174.7983	-0.0027	-0.0034	-0.0034	10.0770	+0.2700	0.0013	-0.0040	10.5623	110 BM-4 U
114	188.8073	+0.0093	-0.0010	-0.0010	10.0715	+0.2645	0.0010	-0.0034	+ .0058	111 BM-4 D
116	165.6948	+0.0008	-5.7662	-0.0042	6.7122	+2.0902	0.0001	-0.0002	+ .0040	139 SM-8
117	146.2029	-0.0041	-12.8528	+0.0022	7.4932	+1.6812	0.0001	-0.0002	20.7549	136 QM-7
118	138.8734	-0.0086	-18.0750	-0.0000	7.1814	+0.2484	0.0005	-0.0011	9.0051	123 BM-8 D
119	124.8779	-0.0041	-18.0767	-0.0017	7.1853	+0.2523	0.0001	0.0001	13.9955	122 BM-8 U

APPENDIX D

TR-II VACUUM SYSTEM PARAMETERS

<u>Material in Vacuum Speed System</u>	<u>Estimated Outgas Rate torr·l/cm²/s</u>	<u>Surface Area cm²</u>	<u>Generated Gas Load torr·l/s</u>	<u>Pumping Speed Required for 3x10⁻⁵ torr·l/s</u>	<u>Ion Pump N₂ Rated Speed for 3x10⁻⁶ torr·l/s</u>
304 SS	1 x 10 ⁻¹⁰	70,000	7 x 10 ⁻⁶	2	11
6061 AL	2 x 10 ⁻⁹	10,000	2 x 10 ⁻⁵	7	39
Kapton Insulation	3 x 10 ⁻⁸	16,000	5 x 10 ⁻⁴	167	928
G-10	1 x 10 ⁻⁷	4,000	4 x 10 ⁻⁴	133	739
TOTAL		100,000	9.27 x 10 ⁻⁴	309	1717

APPENDIX E

TR-II POWER SUPPLIES

1. Bending magnet (two power supplies)

Power Energy Industries
17115-T Kingsview Ave.
Carson, California 90746

600 kW, 3000 A (200 V)
Readout 10 V = 3000 A

2. Quad magnets (eight power supplies)

Christie Laboratories Inc.
2121 W. 117th Street
Cleveland, Ohio 44411

15 kW, 1000 A (15 V)
Readout 100 mV = A

Hookup convention: At the back of the power supply, horizontal bus bars give a horizontal focusing magnet (for + particles). The ammeter readings deflect to the right.

3. Steering magnets

The steering magnets are powered by a LAMPF multi-channel bipolar-output power supply. Each channel is capable of ± 250 A. Power supply currents are measured with shunts that produce a 100-mV signal at 250 A. Signals are amplified at the power supply and sent to CCR where a readout of 10 V = 250 A is used.

Each power supply channel is set up so that a control potentiometer setting of 500 counts gives zero output. For a positive beam (H^+), control potentiometer settings above 500 counts steer the beam up when used for vertical steering. When used for horizontal steering, settings above 500 counts steer the beam to the right.

APPENDIX F

TR-II COOLING-SYSTEM COMPONENTS

1. Taylor Instruments Process Control Division
Sybron Corporation
95 Ames Street
Rochester, New York 14601

Taylor 440R Series pneumatic indicating controller.

2. Transamerica Delaval Inc.
Gems Sensor Division
Plainville, Connecticut 06062

GEMS FS400 bronze flow switches

3. Robert Shaw Controls Company
Fulton Sylphon Division
Box 400
Knoxville, Tennessee 37901

Model VC-230 - 1-1/2 inch diaphragm control valve

4. Aurora Pump
800 Airport Road
North Aurora, Illinois 60542

Aurora pump model 361A, Size 2 x 2-1/2 X7A, 20 H.P., 160 foot
head at 300 GPM.

5. Texas Instruments
34 Forrest St.
Attleboro, Massachusetts 02703

Klixon series 4344 thermostat, stud mount