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Proton Area Enclosure H Upgrade Projects

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Abstract

Several projects which have been planned for implementation in FY81 and FY82 will improve the capability of the Proton Area three-way split for 500 GeV operation and will ultimately lead to 1 TeV capability. These improvements are described here. The discussion includes utility changes, timescales, and modifications to the beam optics. It is demonstrated that the power requirements for 1 TeV operation are within the capabilities of the presently installed substations.

Enclosure H

The ability to provide simultaneously three independent primary proton beams has had much to do with the high productivity of the physics program in the Proton Area. Most of the components involved in the 3-way split are located in Enclosure H.(1) At 500 GeV, many of the magnets are running at peak excitation. Because of the importance of this area to the operation of the Proton Lab, we have given special attention to finding an efficient and reliable solution to the problem of transporting 1 TeV beams through Enclosure H and accomplishing the required three way horizontal split. Several strategies, involving various geometries and combinations of conventional and superconducting magnets, have been evaluated. Our recommendations, summarized here, are similar to but more detailed than those proposed in the Tevatron Upgrade report of March 1978.(2)

The vertical and horizontal trajectories of the 500 GeV beam through Enclosure H are shown in figures la and lb, respectively. Three beams, narrowly separated in the vertical plane, enter Enclosure H. The beams rise at an angle of 8.9 mr relative to the horizontal plane. Three modified B1 magnets(3) bend the beams back to the horizontal. Four Lambertson magnets(4) separate the beams in the horizontal plane by bending the top one to the west by 5.15 mr, the bottom one to the east by 5.15 mr and passing the middle one without deflection. The beams are then allowed to drift approximately 150'. At this point, the center branch is separated laterally from both the east and west branch by about 8 inches. The West branch is deflected horizontally by 8 EPB dipoles so that it emerges from Enclosure H at an angle of 29.8 mr with respect to the incoming beam. The East branch is deflected horizontally by 4 EPB dipoles and emerges at 13.8 mr. The Center beam passes between the first elements of the other two branches and is bent 4.5 mr to the west by 2 EPB dipoles at the downstream end of the hall. Trim magnets in each branch are available for adjusting the vertical spot position at the entry into the "pretarget" areas 2000' downstream. The present arrangement of components is shown in fig. 2a.

We intend to maintain the 1 TeV beams in the existing twelve inch diameter vacuum pipes that now connect Enclosure H to the three pre-target areas. It is therefore necessary to keep the bend points close to their present positions. In addition, we must have adequate lateral separation of the three beams (at least 8 inches) near the middle of the enclosure where the components of the three branches are rather close together. Finally, to improve the efficiency of the physics program in the East branch, we will provide space for a splitting station so that two independent beams can be simultaneously transported to P-East at some future time.

The switchyard design report[5] shows how the 1 TeV beam can be made to approach Enclosure H along the same line as the 500 GeV beam does now. We will intercept this beam 150' further upstream in an extension to Enclosure H, as shown in figure 2b. Four modified Bl's (only one more than in the existing installation) will bend the beam vertically through 6 mr (two-thirds of the required vertical bend). The remaining 3 mr bend is made separately in each of the three beam lines. By splitting the vertical bend in this manner, the effective bend point occurs very close to the present bend point. The vertical trajectory for 1 TeV operation is shown in figure 3a. The horizontal separation of the three beams is accomplished by a string of five Lambertson magnets, preceded by 1 passive Lambertson for shielding and collimation. The added Lambertson magnet and the extra drift space produce enough horizontal separation (10 inches between center and west and 9.0 inches between center and east) between the three beams to accommodate the transverse dimensions of the first few elements of each. The horizontal beam trajectories are shown in figure 3b.

The individual beam lines will be upgraded as follows:

1) In P-West, the 8 EPB dipoles will be replaced by 4 ED/S dipoles. The EPB's are freed for use in P-East and P-Center.

2) In P-Center, two of the EPB's released from P-West are added.

3) In P-East, four of the EPB's released from P-West are added.

The remaining 3 mr vertical bend is accomplished by rolling the dipoles: In P-West, by 6.7°, in P-Center by 33.7°, and in P-East by 15°.

This solution has been chosen for several reasons: 1) It involves no new magnet design, 2) Only conventional magnets are used at known high loss points, 3) It is economical in its consumption of power, 4) Installation costs are low, 5) It uses the components already existing in the enclosure very efficiently, 6) It provides sufficient room for collimators and shielding which may be required in order to operate the ED/S dipoles in the West beam at high intensities.

The present maximum amount of vertical trim power for each beam line in Enclosure H is 8.5kG-ft., 70% of which is used during normal 400 GeV operation. Since both the existing and the 1 TeV beam trajectories entering Enclosure H are the same, one linearly scales the bending power with the Proton beam energy to determine the bend strength for 1 TeV operation. When this is done, the necessary vertical trim power is 20.5kG-ft. The 1 TeV upgrade of Enclosure H will require two Eartly trim[6] magnets, one each in the Center and East beam line, and 1 EPB dipole in the West line.

The refrigerator that provides helium to the four (4) ED/S dipoles for the West branch will be located in an extension to the P-1 Service Building. To facilitate access to the road that runs along the East side of the Neutrino berm, one substation will be relocated to a free space on an existing pad. Figures 4a, b show the arrangement of components in and around the P-1 Service Building before and after the upgrade.

The 90' extension on the downstream end of the enclosure will contain the final elements of P-Center and P-East, and at some future time will accommodate the four (4) electrostatic septa which will split the beam in the East line. The four (4) septa will produce a 1" separation of the two beams at a distance halfway between Enclosure H and the P-East pretarget area. A new enclosure located at that point will contain Lambertson magnets which separate the beams in the horizontal plane. A quadrupole doublet just upstream of the septa can be used to minimize the spot size at the Lambertsons.

Power and Utilities

The electrical power needed to operate the components at 1 TeV will be supplied by the two existing substations. Technical Appendix I presents a complete breakdown of the power requirements at 1 TeV.

Water System

The present LCW and ICW supply is adequate for 1 TeV operation. Details of the water system are given in Technical Appendix II.

Cryogenic System

The requirements for refrigeration are given in Technical Appendix III. The major uncertainty in the calculation is the heat load due to the beam halo. This can, of course, vary depending on the conditions in the Proton switchyard. The estimate of 8 watts per magnet as the beam-induced heat load is very conservative.

The string of ED/S dipoles requires a lead box, a turnaround box and about 200' of transfer line.

One attractive feature of the proposed layout of the enclosure is that 150' of space is available for collimators and shields to reduce beam halo. The installation schedule described below provides for some early running with a 500 GeV version of the new configuration. During this operating period, we will gain valuable experience in the operation of ED/S dipoles in Enclosure H and with possible problems from beam loading.

Radiation Safety

An important feature of the proposed layout is that the additional space will allow the vertical bend, four modified B1 magnets, to be moved away from the access way and provide space for additional shielding. Presently, the residual radioactivity of these magnets is about 400 mrem/hr at one foot; at higher intensities in West it will be several rem/hr. Similarly, the fixed aperture collimator upstream of the Lambertson magnets will be several rem/hr. The additional space will also allow this to be shielded and to be placed farther away from active components.

Presently, the radioactive gases produced in Enclosure H are either vented to the outside by a fan located in the downstream area (a major loss area), or vented into P-1 Service Building with the fan off. The proposed layout would allow a ventilation fan to be installed in the upstream emergency exit. The travel time of the radioactive gases from the loss point to the environment would be lengthened and thereby result in lower radiation exposure offsite.

Installation

New magnets to be installed in Enclosoure H are all ten-foot long, conventional magnets with the exception of the four ED/S dipole magnets in the P-West line. The fifteen-foot long drop hatch in the P-1 Service Building provides access to a tunnel leading to Enclosure H. The ED/S dipole magnets must be lowered through the fifteen-foot drop hatch with the use of a positioning fixture. Transferring the magnets around three corners of the tunnel leading to Enclosure H is possible, but care is required due to limited clearance in the tunnel.

Construction and Equipment Requirements

Table 1 summarizes the construction requirements for these projects including the P-1 Service Building extension. Table 2 summarizes the equipment requirements including magnets, power supplies, cryogenic equipment, transfer lines, and magnet supports.

Time Schedules

The proposed new layout of Enclosure H is superior to the present arrangement, even for 500 GeV operation. The high loss points near the B1 magnets and the Lambertsons are moved away from the main entrance. The longer drift space downstream of the Lambertsons will accommodate additional cleanup collimators. Figure 5 gives the beam line layout for 500 GeV operation in the new configuration. The only new elements are two (2) ED/S dipoles and the associated cryogenic components. Only the modified B1 dipoles and Lambertsons need to be moved. The downstream components need only to be rolled by the appropriate angles around the beam axis. In this arrangement we can operate the West branch with or without the superconducting dipoles. During this period, we will study the new optics and commission the superconducting magnets.

We envision the following schedule:

1) October 1980 - November 1980:	P-1 Service Building expansion.
2) December 1980 - June 1981:	Installation of refrigerator for Enclosure H cryogenic dipoles.
3) June 1981 - February 1982:	Construction of Enclosure H extensions Reconfiguration of Enclosure H for improved 500 GeV operation.
4) February 1, 1982 - June 1982:	Operation of Enclosure H in new configuration.
5) June 1, 1982:	Begin reorganization of components and installation of new components for 1 TeV operation.
6) Summer 1982:	Begin operation at 1 TeV.

APPENDIX I: POWER AND UTILITIES

Existing Installation - 500 GeV Operation

The existing P-1 Service Building contains four 500 KW and four 240 KW power supplies feeding conventional transport magnets in Enclosure H. All power supplies are pulsed and the system is capable of transporting beams to the three proton beam lines at a peak energy of 500 GeV. The 500 GeV pulse period is 12 seconds long with a 0.5 second flattop. If the power supplies were run on straight DC there would be insufficient electrical power to handle the load. Running at energies below 500 GeV requires about the same RMS loads, because shorter pulse periods and longer flattop time are generally used during this mode of operation. All P-1 Service Building power supplies are fed from two 1500 KVA substations. These substations also supply power to (1) conventional P-1 Service Building loads, such as lights, pumps, etc., and (2) a 400 A service which supplies the Neutrino Target Service Building. Each 1500 KVA substation has a rated load line current of 1800 ARMS at 480 VAC and a 3-phase peak load line current capacity of about 3000 A per phase during ramping. Exceeding 3000 A per phase would result in an excessive voltage drop (larger than 10%). The equipment is not designed for voltage drops in excess of 10%. The present P-1 Service Building loads at 500 GeV with a 12 second pulse period and 0.5 second flattop are calculated to be:

Power Supplies - peak AC line load	4000 A
Building - peak AC line load (estimated)	400 A
Total peak AC line current	4400 A
Total RMS line current	2400 ARMS
Total magnet losses	500 KW

Future Installation - 1 TeV Operation

To upgrade from 500 GeV to 1 TeV operation requires a mixture of conventional and superconducting magnets in an expanded version of Enclosure H. These magnets are fed from: A) Five 500 KW power supplies, B) Three 240 KW power supplies, and C) Two 55 KW power supplies located in the P-1 Service Building.

A pulse period of 60 seconds for 1 TeV operation is used for substation load calculations. A current rise time of 6.4 seconds from 0 to flattop value (1 TeV) is chosen so that the ceiling voltage of the power supplies is not exceeded. The single line drawings shown on figure 6a, 6b, 6c, and 6d show the results of detailed load calculations.

The future P-1 Service Building loads for a 60-second pulse period at 1 TeV operation are calculated to be:

Power Supplies - peak AC line load	3600 A
Building - peak AC line load	400 A
400 H.P. compressor	500 A
Total peak line current	4500 A
Power Supplies - RMS AC line load	2300 ARMS
Building - RMS AC line load	400 ARMS
400 H.P. compressor (Max)	500 ARMS
Total RMS line current	3200 ARMS
Total magnet losses	400 KW

The present AC capacity at the P-1 Service Building is adequate for 1 TeV upgrade using a 60-second pulse period. The AC and DC distribution system will need modification as a result of the increased number of power supplies, magnets and the addition of a 400 H.P. helium compressor. This compressor is required for the operation of the superconducting magnets. Table 3 summarizes the power requirements for Enclosure H in its present configuration and for the proposed 1 TeV configuration.

APPENDIX II: WATER SYSTEM

P-1 Service Building Industrial Cooling Water (I.C.W.) is used to cool the helium refrigerator compressor, and the Low Conductivity Water (L.C.W.) through the heat exchanger. The pressurized L.C.W. system is a closed loop system which cools the conventional magnets in H Enclosure and their associated power supplies in the P-1 Service Building.

I.C.W. System

The I.C.W. is supplied by a 100 H.P. pump via the 20 inch storm feeder main line from the accelerator main ring cooling ponds. This 20-inch line tees down to an 8-inch line and continues to the P-1 Service Building. The 8-inch I.C.W. line in the P-1 Service Building will branch with a 3-inch I.C.W. line to provide cooling for the helium refrigerator compressor while the 8-inch I.C.W. line continues to the tube and shell heat exchanger to provide I.C.W. cooling for the L.C.W. A 100 H.P. Aurora pump provides a discharge capacity of 1370 GPM at 87 PSI. Upon leaving the P-1 Service Building the I.C.W. discharge can either be released into a swale leading to the No. 9 ditch or into the I.C.W. return system.

For 500 GeV operation, 600 GPM are used. At 1 TeV, the additional magnets and helium refrigerator compressor need 300 GPM more, giving a total demand of 900 GPM. This somewhat increased demand is well within the capacity of the existing supply system.

L.C.W. System

The L.C.W. System is a pressurized closed loop system. A nitrogen gas pressure system provides net positive suction head pressure through a 163 gallon expansion tank to the inlet side of a 60 H.P.

Ingersoll Rand pump, with a second Ingersoll Rand pump as a backup in case of emergency. The pump has a maximum flow rate capacity of 380 GPM at 130 PSI providing 2000 KW of L.C.W. cooling capacity with an L.C.W. temperature differential of 20^{O}C across the heat exchanger using 80^{O}F I.C.W. at the inlet to the heat exchanger. The cooling requirement in H Enclosure and the P-1 Service Building for the present 500 GeV configuration of magnets and power supplies is 850 KW with a 160 GPM flow rate. The 1 TeV configuration requires 1000 KW of L.C.W. cooling capacity with a 190 GPM flow rate for magnets, power supplies and water-cooled bus. The individual component requirements are listed and totaled in Table 4. A total of 1000 KW of L.C.W. cooling is required for the 1 TeV configuration. This requirement of 1000 KW is far below the 2000 KW capacity of the present water system.

APPENDIX III: ENCLOSURE H CRYOGENIC REQUIREMENTS

The Enclosure H upgrade will include the installation of two ED/S dipoles in the P-West bend string for 500 GeV capability. These magnets will be connected to a refrigeration plant in an expanded P-1 Service Building by approximately 200 feet of transfer line. The static heat loads in the liquid helium system are presented for 500 GeV operation at 10^{13} protons per 10-second machine cycle.

2 ED/S dipole magnets at 7 watts/magnet (7)	14 watts
1 high current lead pair at 10 watts + 14 l/hr (8)	50
1 set of lead and turn-around boxes (7)	20
200' liquid helium transfer line at 0.05 watts/ft (9)	10
Thermal beam loading (worst case) (10)	16
Total 4^{o}K thermal load at 500 GeV	110 watts

For 1 TeV operation, two additional dipoles are added and the cycle time is increased to 60 seconds. This then adds the following load at 10^{13} protons/60 second pulse.

2 ED/S dipole magnets at 7 watts/magnet	+14 watts
Thermal beam loading (note longer cycle time)	-11 watts
Thermal loads at 500 GeV	110 watts
Total 4^{o}K thermal load at 1 TeV	113 watts

The refrigeration requirements fall slightly higher than the capacity of a single CTI 1400 refrigerator with three compressors (95 watts design specifications). A satellite refrigerator (500 watts) has excess capacity. The solution chosen for the superconducting M6 upgrade tests, namely two CTI 1400 refrigerators, along with 6 or 8 compressor units, would provide reliable operation by allowing a complete cold box or up to half of the compressors to be off line for servicing while the on-line system could barely keep up with the magnet and transfer line losses. To improve compressor reliability, a small screw compressor would be chosen instead of purchasing multiple CTI 1400 compressors. A surplus liquid helium reserve could be produced while both refrigerators were operational in anticipation of such continued operation with only one system. Meson Laboratory operating experience indicates that a large manpower investment is requirement to operate such a system reliably[11].

Installation of a satellite refrigerator will be considered as a competitive option if experience at P-4 and elsewhere indicates reliable operation with minimal attention from operation crews. This option will also allow for the upgrade of the P-East and P-Center bend strings if that becomes desirable at some later date.

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We also wish to thank J. Peoples who has challenged us often to improve our designs. His efforts have led us to the most efficient use of resources in this project.

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2. B. Cox, P. Garbincius, J. Lach, C. T. Murphy, and K. Stanfield, Proton Laboratory 1 TeV Upgrade, (1978).

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4. J. Pachnik and A. Tunner, Magetic Field Measurement in 3-Way Split Magnet, Fermilab FM-571 (1975).

5. R. Dixon, Switchyard Design Report (1979).

6. D. Eartly, Specifications in the 2.87-5.5-60 Laminated Steering Dipole, Proton Department Internal Document (unpublished).

7. Superconducting Accelerator Design Report, P70, 1979.

8. Taken from reference 6 and conversion of liters/hr to watts for satellite refrigerator system.

9. P. O. Mazur, estimate.

10. Estimated using a) worst case calorimetric measurements downstream of extraction septa by H. Edwards, et al., Fermilab TM-683 (1976) and IEEE MAG-13, 667 (1977) and b) calculations by A. VanGinneken, Fermilab TM-685 (1976).

11. H. Haggerty, Private communication.

TABLE 1

NEW CONSTRUCTION

"H" ENCLOSURE & SERVICE BUILDING

ITEM	LOCATION	SIZE
1. Stair & tunnel revision (preparation for Item 2)	Cross over tunnel to "J" Enclosure running under "H" Enclosures	
2. "H" Enclosure upstream extension	South end of existing "H" Enclosure	7' wide x 7' high x 150' long
3. Escape Hatch	Center of upstream end of "H" Enclosure	3' wide x 3.5' long opening to outside with 3' wide x 7' high tunnel to "H" Enclosure
4. "H" Enclosure downstream extension	North end of existing "H" Enclosure	10' wide x 7' high x 90' long
5. DC power conduit penetration to "H" Enclosure from P-1 Service Building	Center point of "H" Enclosure	(8) 4" rigid conduit in concrete
6. Minimum electrical required	"H" Enclosure	Receptacles, lighting, exit signs, etc.
7. Service Building addition	East side running parallel to existing P-1 Service Building	16' wide x 64' long 1024 ft.^{2}

TABLE 2

MAGNETS & ASSOCIATED EQUIPMENT

IN "H" ENCLOSURE A

	Description	Required 500 GeV	Required 1 TeV	Units Existing
1.	ED/S Dipole	2	4	0
2.	EPB Dipole	13	13	14
3.	Modified B1	3	4	3
4.	Trim	2	2	4
5.	Three-Way Lambertson	4	5	4
6.	Passive Lambertson	1	1	1
7.	Collimator	3	3	3
8.	Lead Box	1	1	0
9.	Turn Around Box	1	1	0
10.	Vacuum Pump Station	1	1	0
11.	Magnet Support	7	14	

POWER SUPPLIES

P-1 SERVICE BUILDING

12.	55KW Power Supply	2	2	0
13.	240KW Power Supply	3	3	4
14.	500KW Power Supply	4	5	4

TABLE 3

Item	P-1 Loads and AC Capacity: Present 500 GeV	P-1 Loads and AC Capacity: Future 1 TeV
Installed AC Capacity	2 x 1500KVA subst. rating (2 subst.)	Same
	3600 A/ϕ RMS	Same
	6000 A/ϕ peak	Same
Total AC Line Load Current	2400 A/ϕ RMS	3200 A/ϕ RMS
	4400 A/ϕ peak	4500 A/ϕ peak
Reserve AC Capacity	1200 A/ϕ RMS	400 A/ϕ RMS
Total Magnet Losses to Cooling Water	$\sim$ 500 KW	$\sim$ 500 KW
Pulse Period	12 sec.	60 sec.
	0.5 sec. flattop	20 sec. flattop
Number of PS 500 KW	4	5
" " " 240 KW	4	3
" " " 55 KW	0	2

TABLE 4a

L.C.W. REQUIRED FOR MAGNETS AND POWER SUPPLIES - H ENCLOSURE

FOR PRESENT 500 GeV

Beam	Magnet	No. in String	G.P.M. per Magnet	G.P.M. Total	Bus Cooling G.P.M.	Power Supply	Power Supply G.P.M.	Total G.P.M. Per Line
P	Modified B1	3	9.6	28.8		500	5	
P	Lambertson 3-way	4	2.6	10.4		240 240	5 5	54.2
West	Trim	1	4.7	4.7				
West	EPB Dipoles	8	4.7	37.6		500 500	5 5	52.3
Center	EPB Dipole	2	4.7	9.4		240	5	19.1
Center	Trim	1	4.7	4.7				
East	EPB Dipole	4	4.7	18.8		240	5	33.2
East	Trim	2	4.7	9.4				
								158.8 G.P.M. L.C.W. Total

TABLE 4b

L.C.W. REQUIRED FOR MAGNETS AND POWER SUPPLIES - H ENCLOSURE

FOR 1 TeV

Beam	Magnet	No. in String	G.P.M. per Magnet	G.P.M. Total	Bus Cooling G.P.M.	Power Supply	Power Supply G.P.M.	Total G.P.M. Per Line
P	Modified B1	4	9.6	38.4		500	5	66.4
P	Lambertson 3-way	5	2.6	13		240 240	5 5	
West	EPB Dipole	1	4.7	4.7		240	5	29.7
West	ED/S	4	0	0	15	500	5	
Center	EPB Dipole	4	4.7	18.8		500	5	28.5
Center	Trim	1	4.7	4.7		55	Air	
East	EPB Dipole	4	4.7	18.8		500	5	
East	EPB Dipole	4	4.7	18.8		500	5	52.3
East	Trim	1	4.7	4.7		55	Air	
								176.9 G.P.M. L.C.W. Total

FIGURE CAPTIONS

1. a) Vertical trajectory b) Horizontal trajectory of 500 GeV primary proton beam through Enclosure H. X, Y coordinates and elevations are Dusaf coordinates.

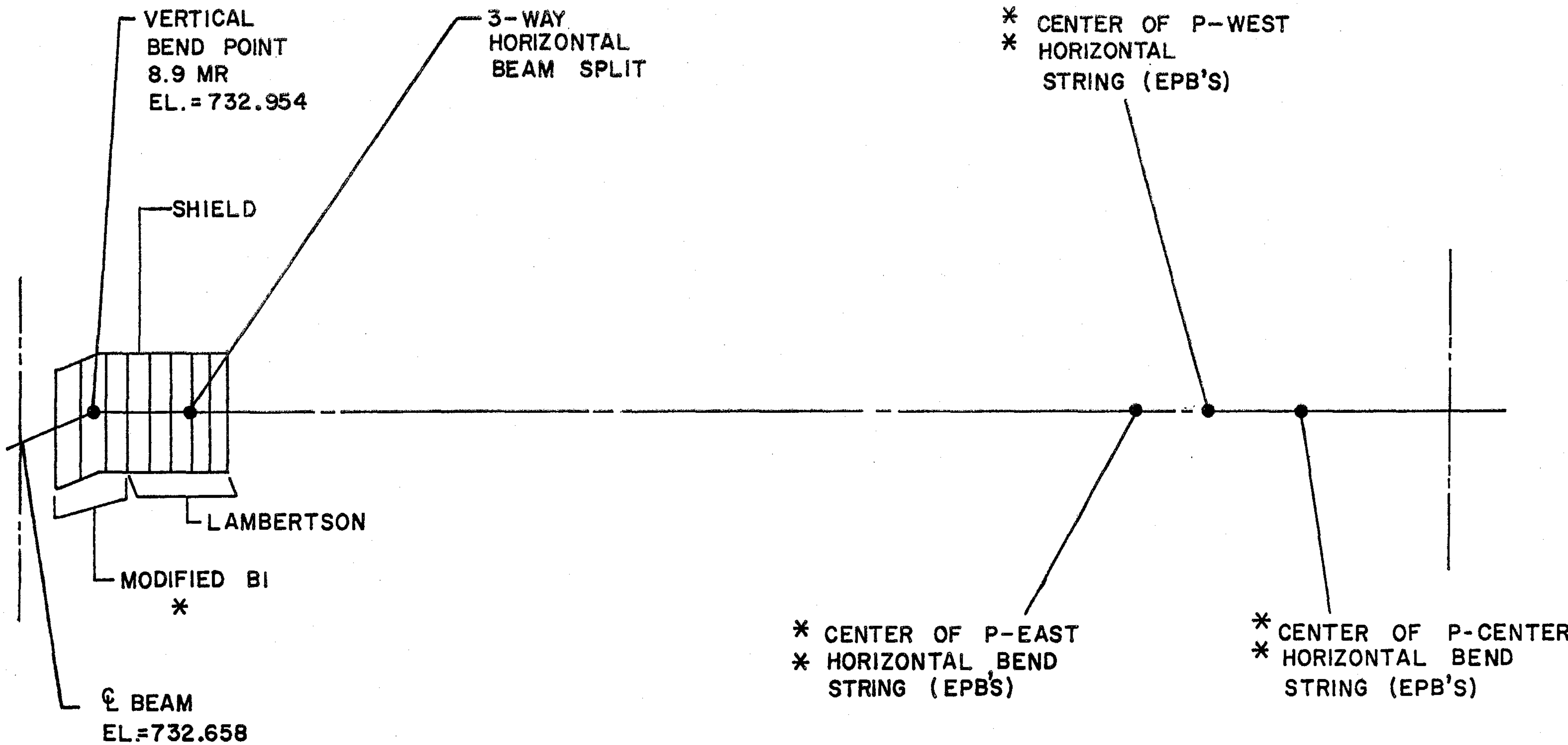
2. a) Present arrangement of components b) Proposed new arrangement of components in enlarged enclosure.

3. a) Vertical trajectory b) Horizontal trajectory of 1 TeV primary proton beam through enlarged enclosure.

4. Arrangement of components in and around the P-1 Service Building. a) before and b) after the upgrade.

5. Arrangement of components for 500 GeV operation in new configuration.

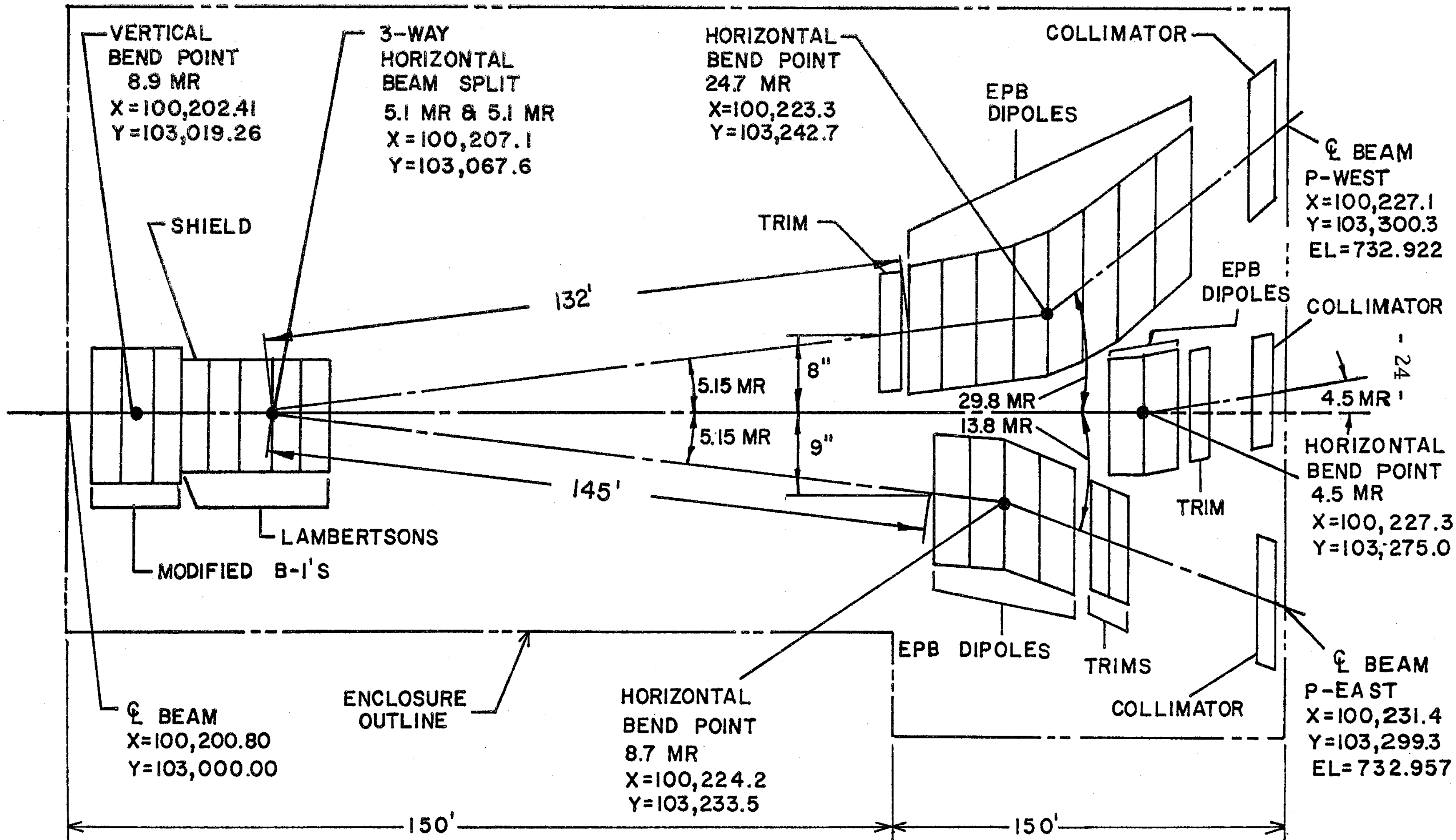
6. Magnet-by-magnet calculation of power requirements at 1 TeV.



* THE THREE BEAMS ARE SEPARATED
~ 1 1/2" VERTICALLY ENTERING BI'S

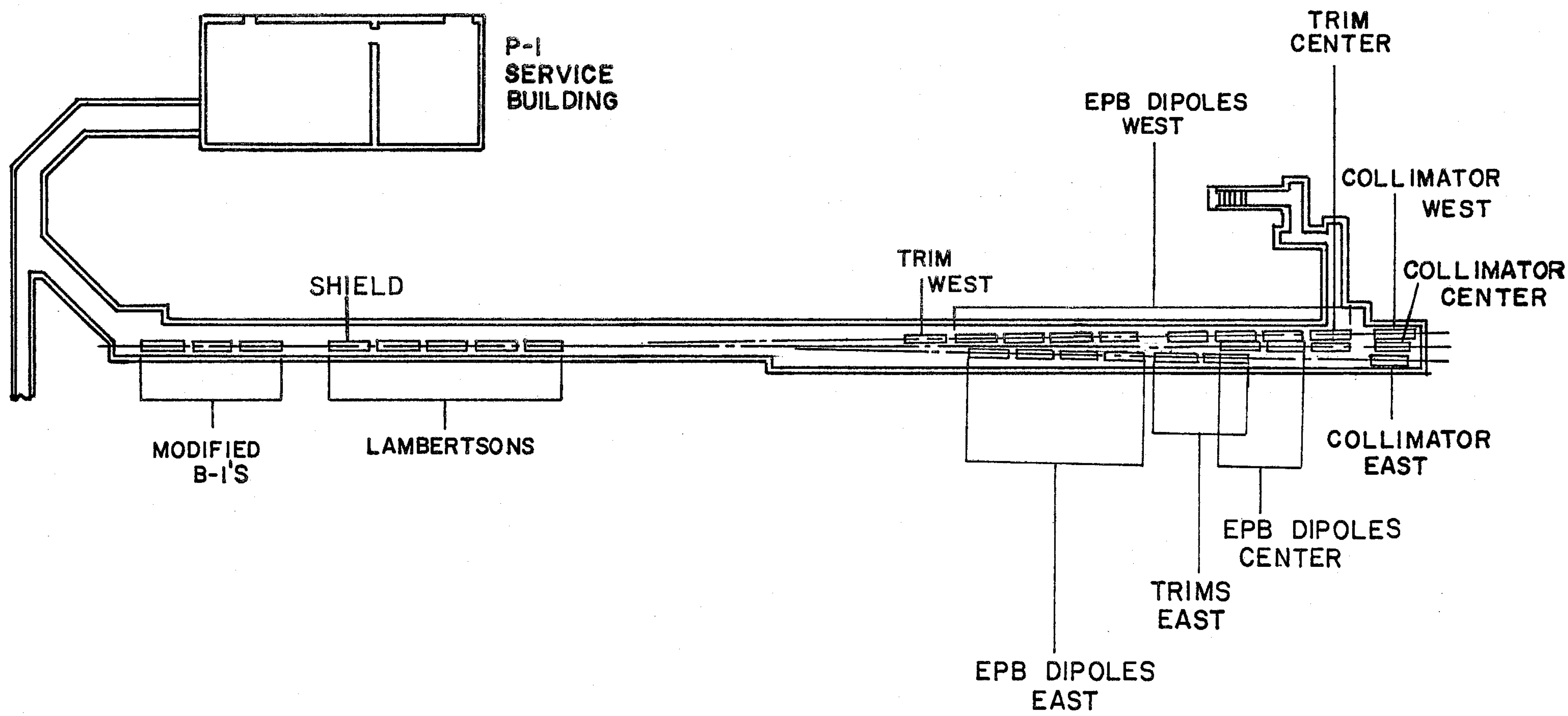
* MAGNETS FOR P-EAST, CENTER &
* WEST BEND SHOWN ON FIGURE 1b

EXISTING 500 GeV
H ENCLOSURE
VERTICAL TRAJECTORIES
OF P-EAST, CENTER & WEST
FIGURE 1a



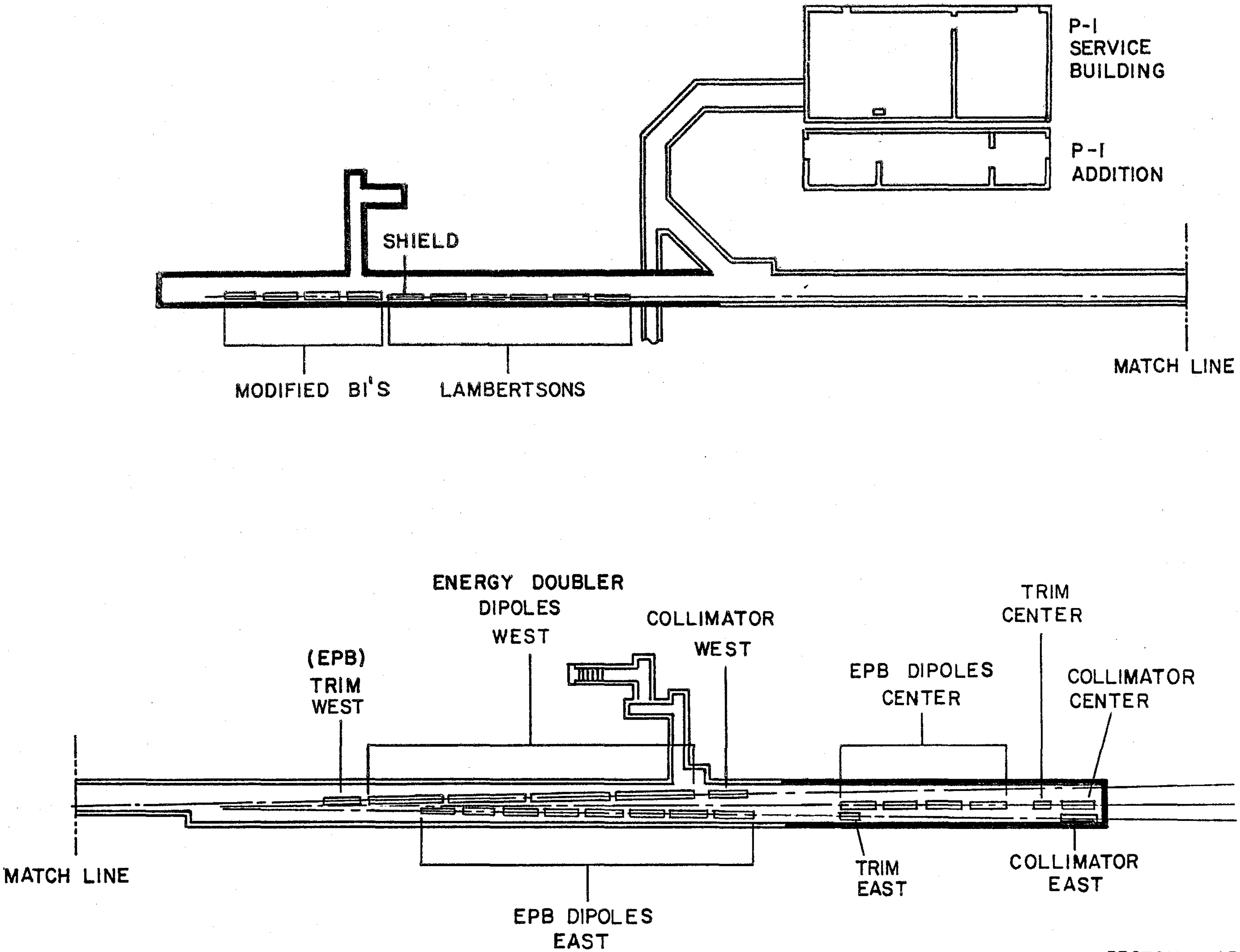
EXISTING 500 GeV H ENCLOSURE HORIZONTAL TRAJECTORIES OF P-EAST, CENTER & WEST

FIGURE 1b



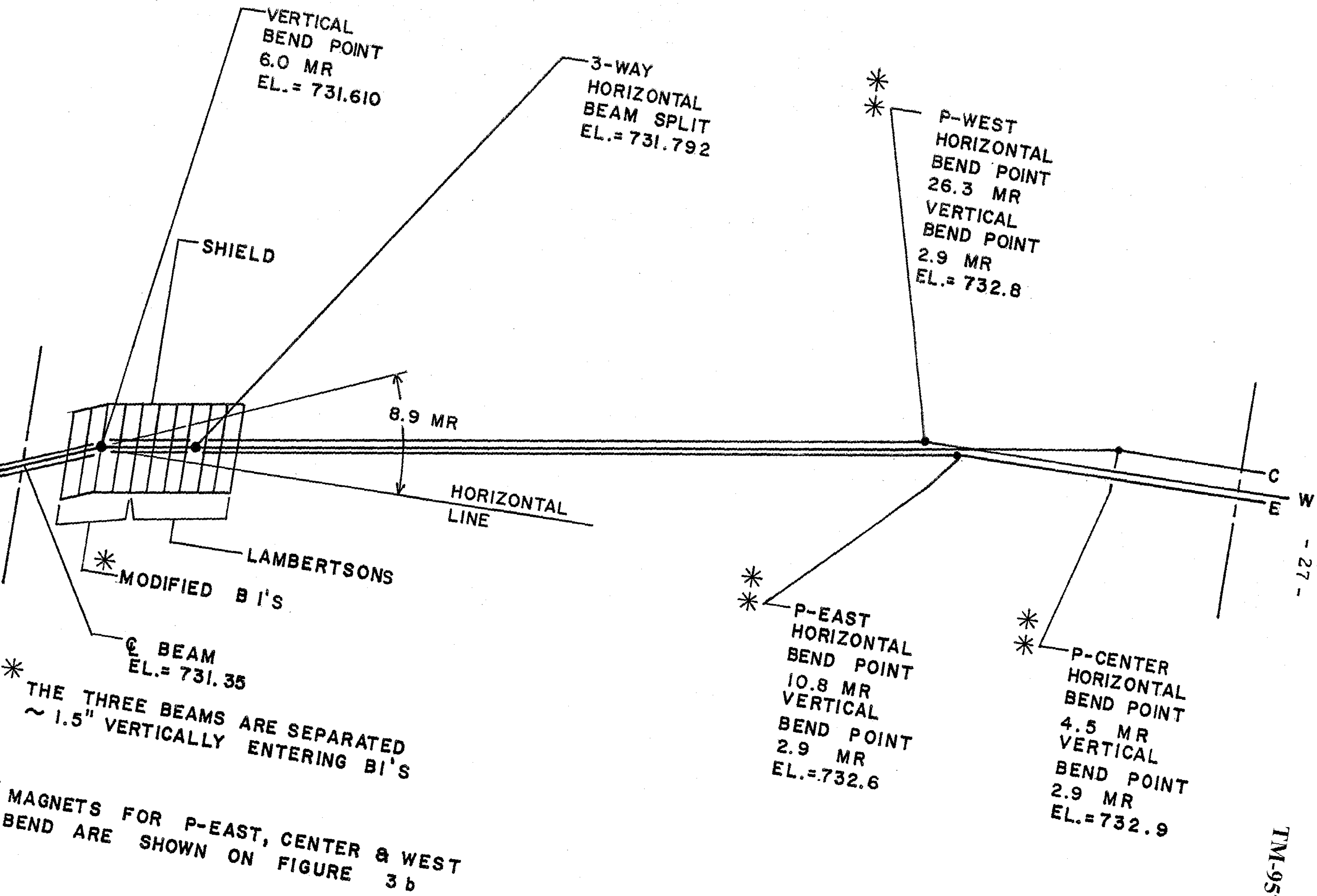
PROTON LAB
EXISTING ENCLOSURE H
500 GeV CONFIGURATION

FIGURE 2a

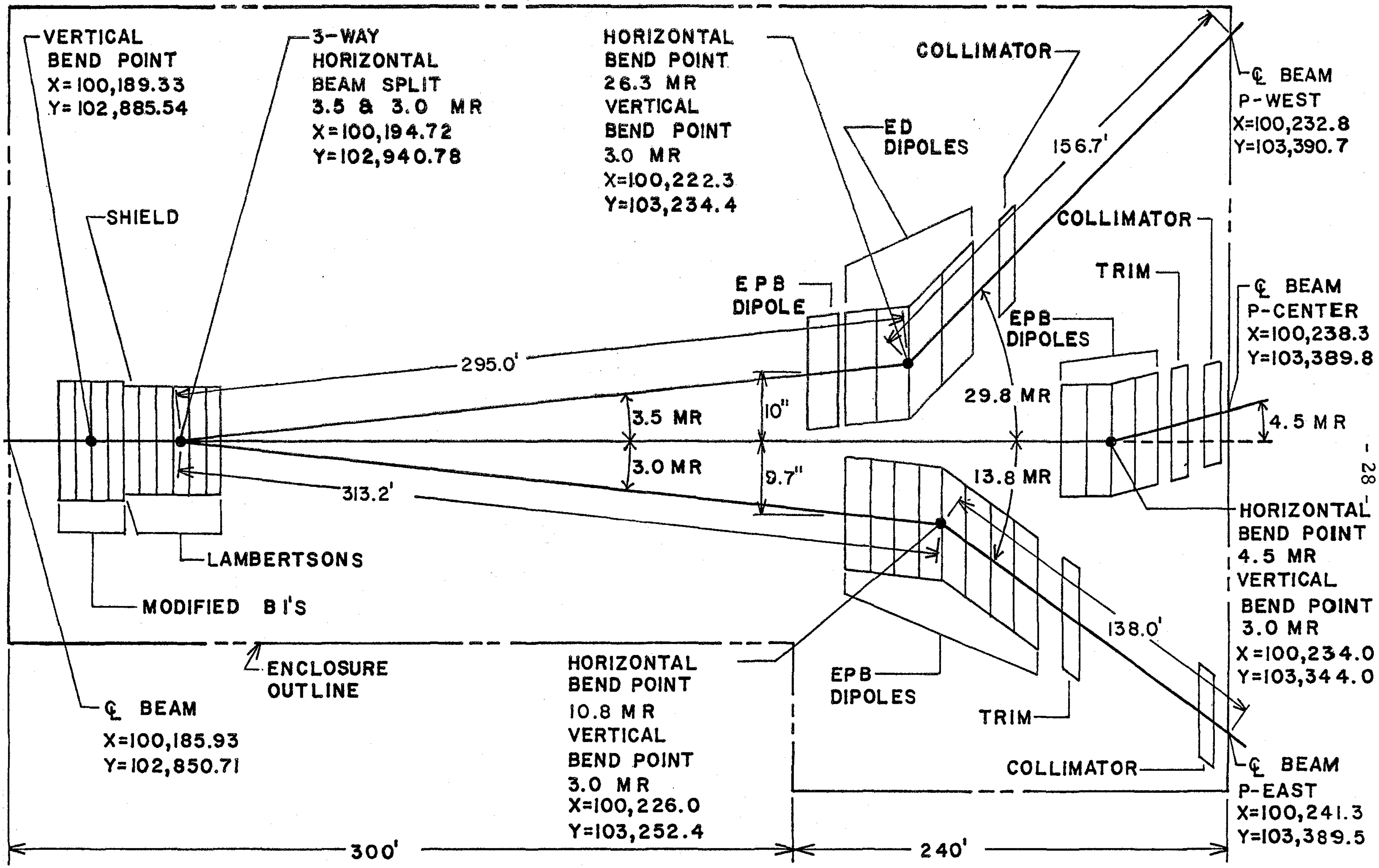


PROTON LAB
EXTENDED ENCLOSURE H
I TEV CONFIGURATION

FIGURE 2b

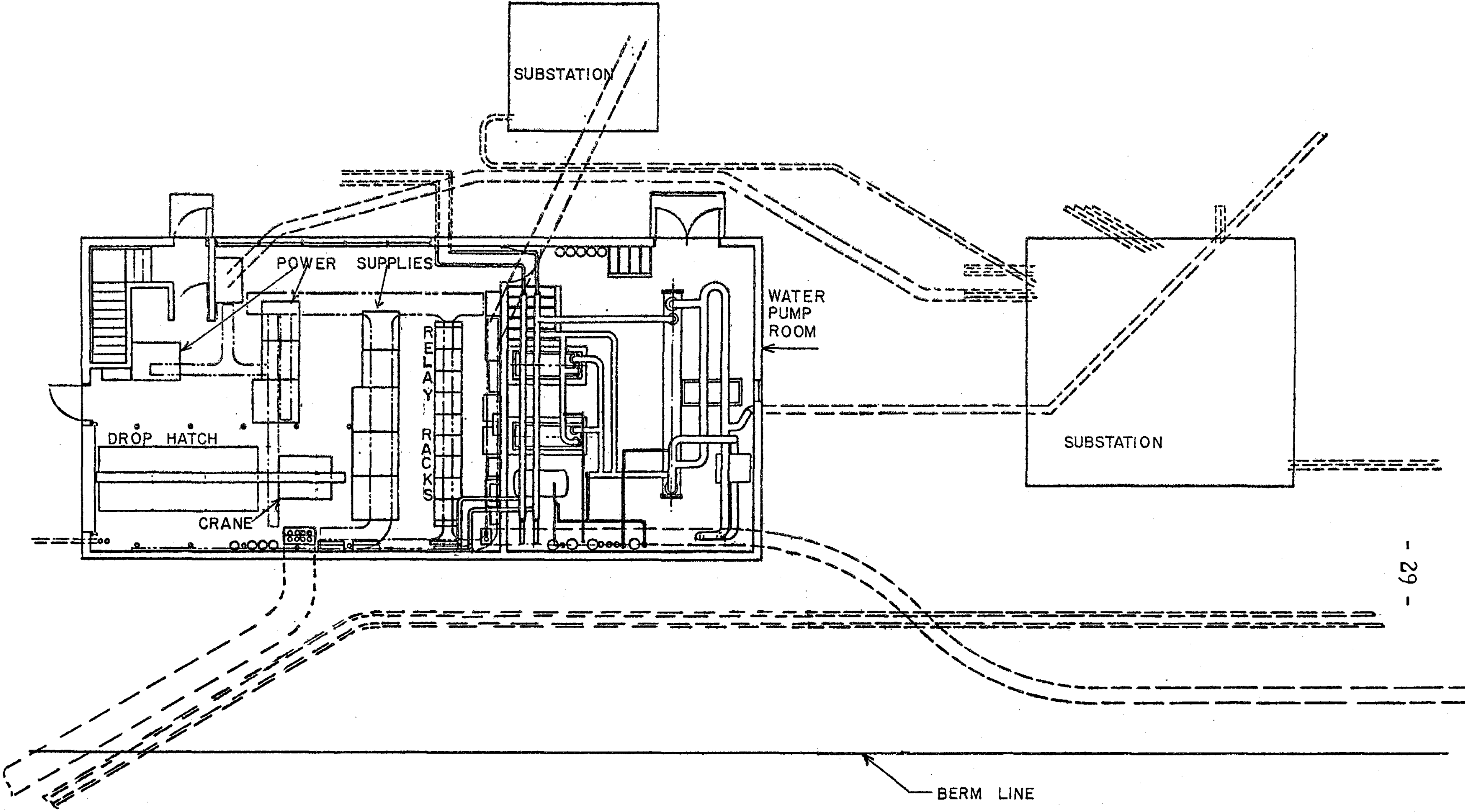


1 TeV
H ENCLOSURE
VERTICAL TRAJECTORIES
OF P-EAST



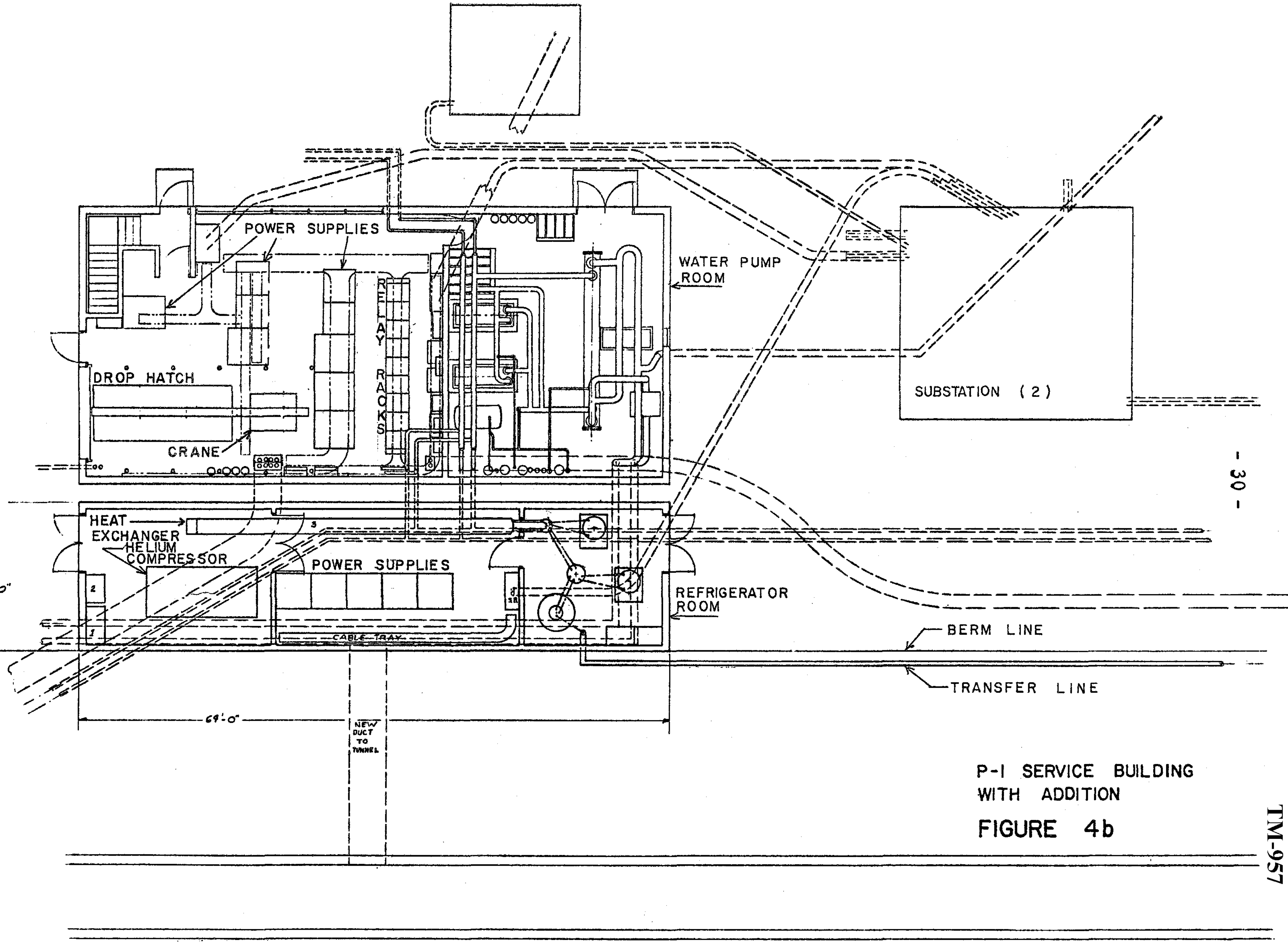
1 TeV
H ENCLOSURE
HORIZONTAL TRAJECTORIES
OF P-EAST, CENTER & WEST

FIGURE 3b



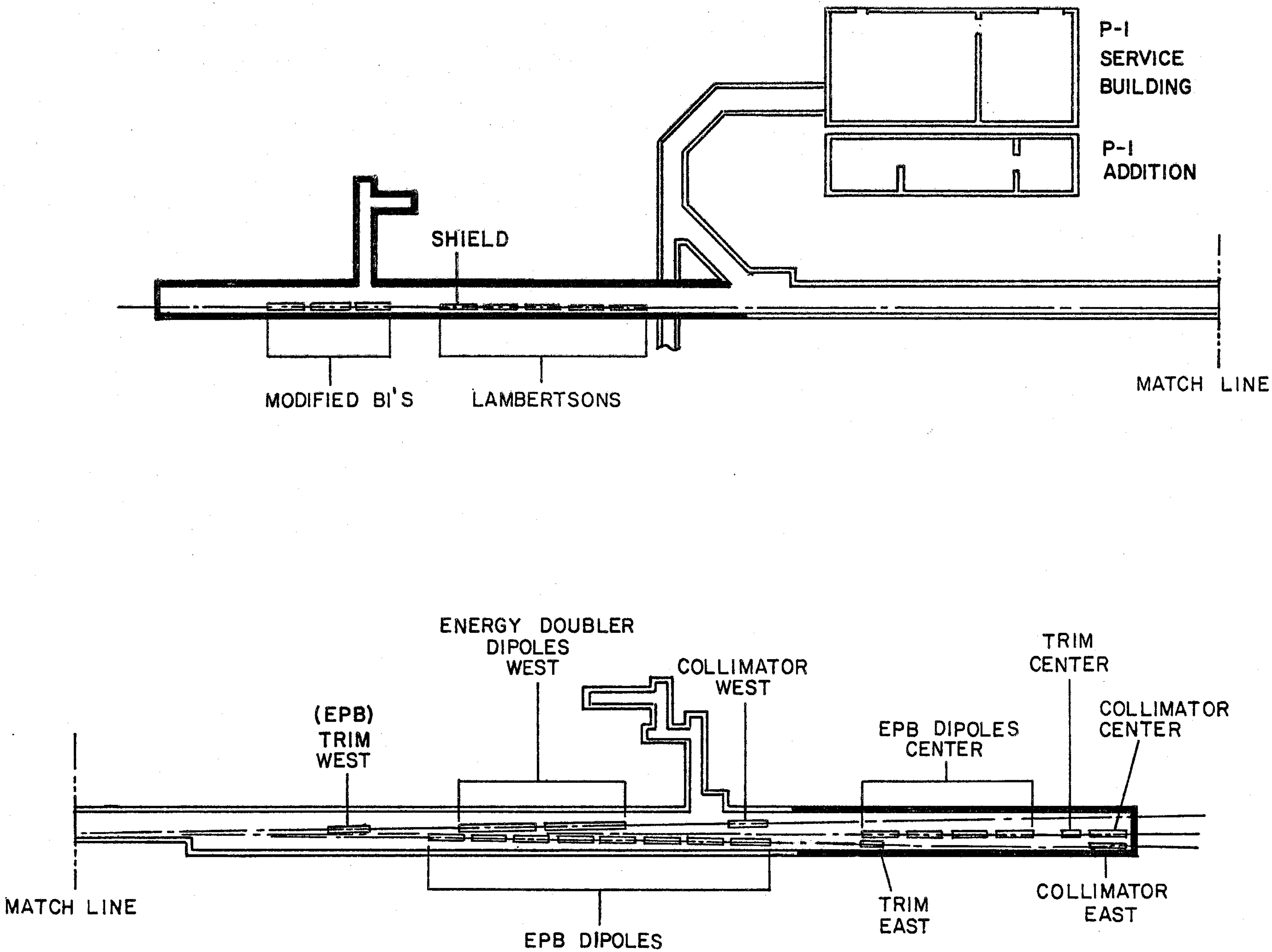
EXISTING
P-1 SERVICE BUILDING

FIGURE 4a



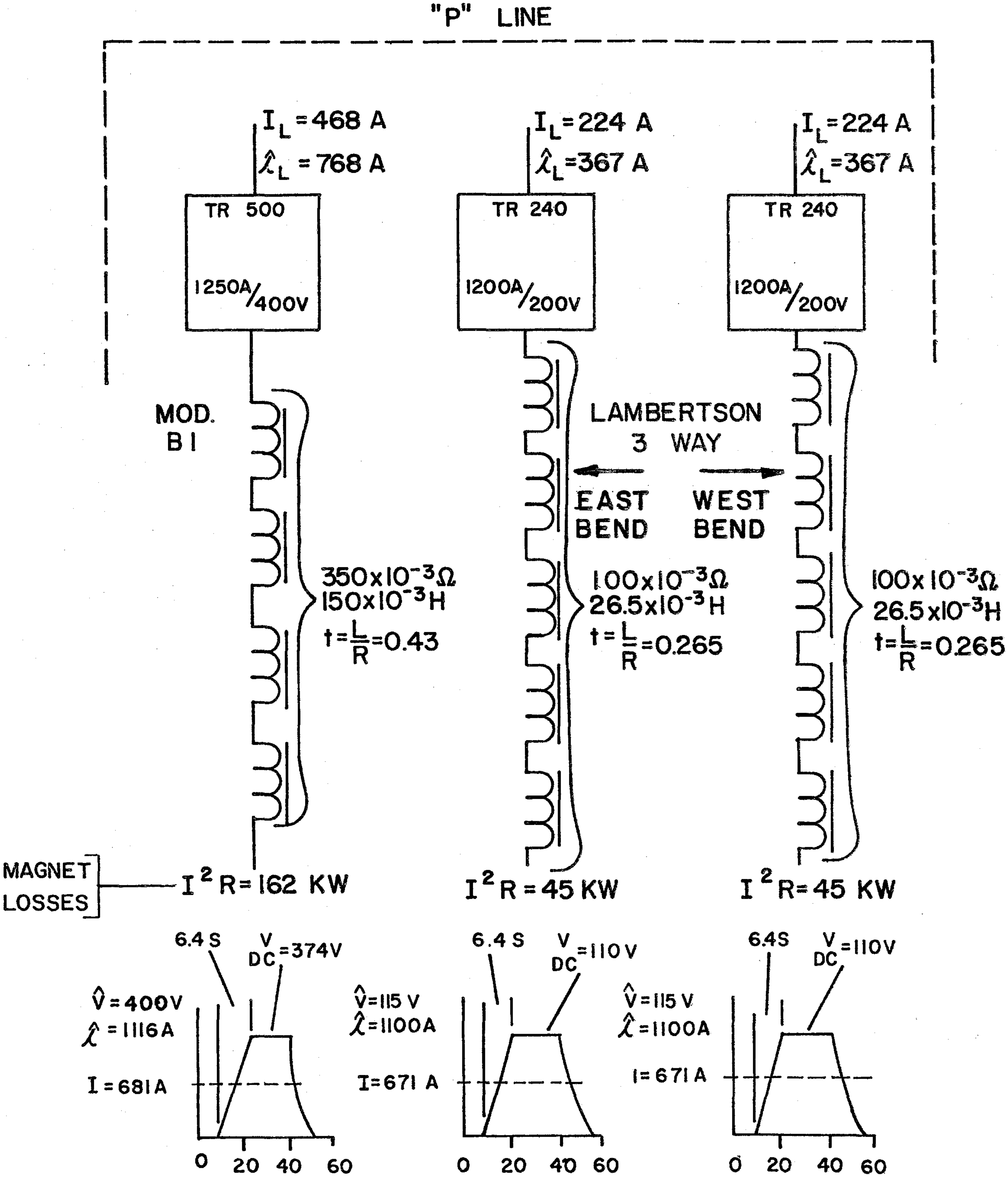
P-I SERVICE BUILDING WITH ADDITION

FIGURE 4b



PROTON LAB
EXTENDED ENCLOSURE H
NEW 500 GEV CONFIGURATION

FIGURE 5



TR 500 = 500 KW P. S.
TR 240 = 240 KW P. S.
L 55 = 55 KW P. S.
$\hat{\lambda}$ DENOTES PEAK VALUE
I DENOTES RMS VALUE

FIGURE 6a

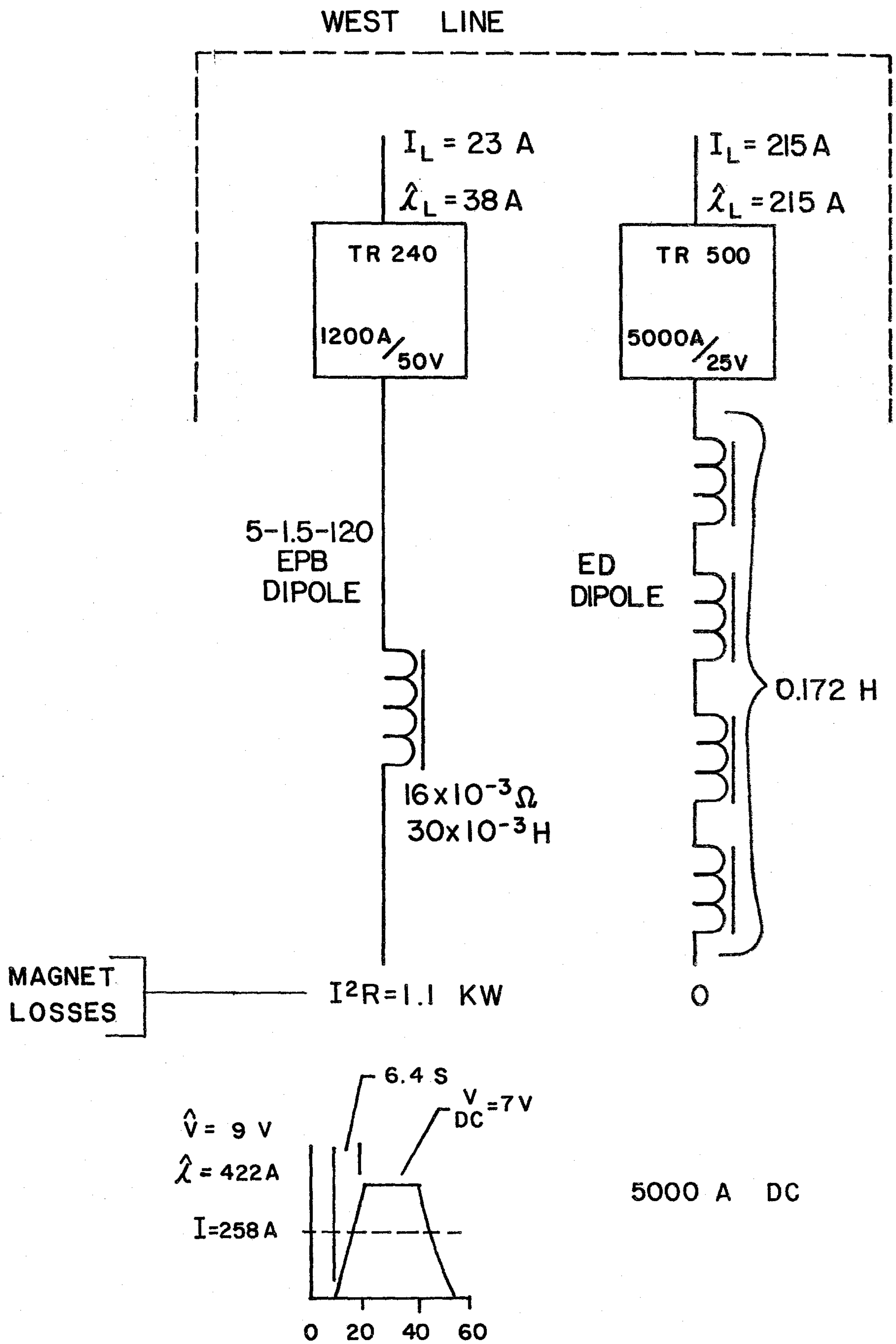

WEST LINE
I_L = 23 A
Î_L = 38 A
TR 240
1200A/50V
5-1.5-120
EPB
DIPOLE
16x10^-3 Ω
30x10^-3 H
I_L = 215 A
Î_L = 215 A
TR 500
5000A/25V
ED
DIPOLE
0.172 H
MAGNET
LOSSES
I²R = 1.1 KW
0
6.4 S
V_DC = 7 V
V̂ = 9 V
Î = 422 A
I = 258 A
0
20
40
60
5000 A DC

FIGURE 6b

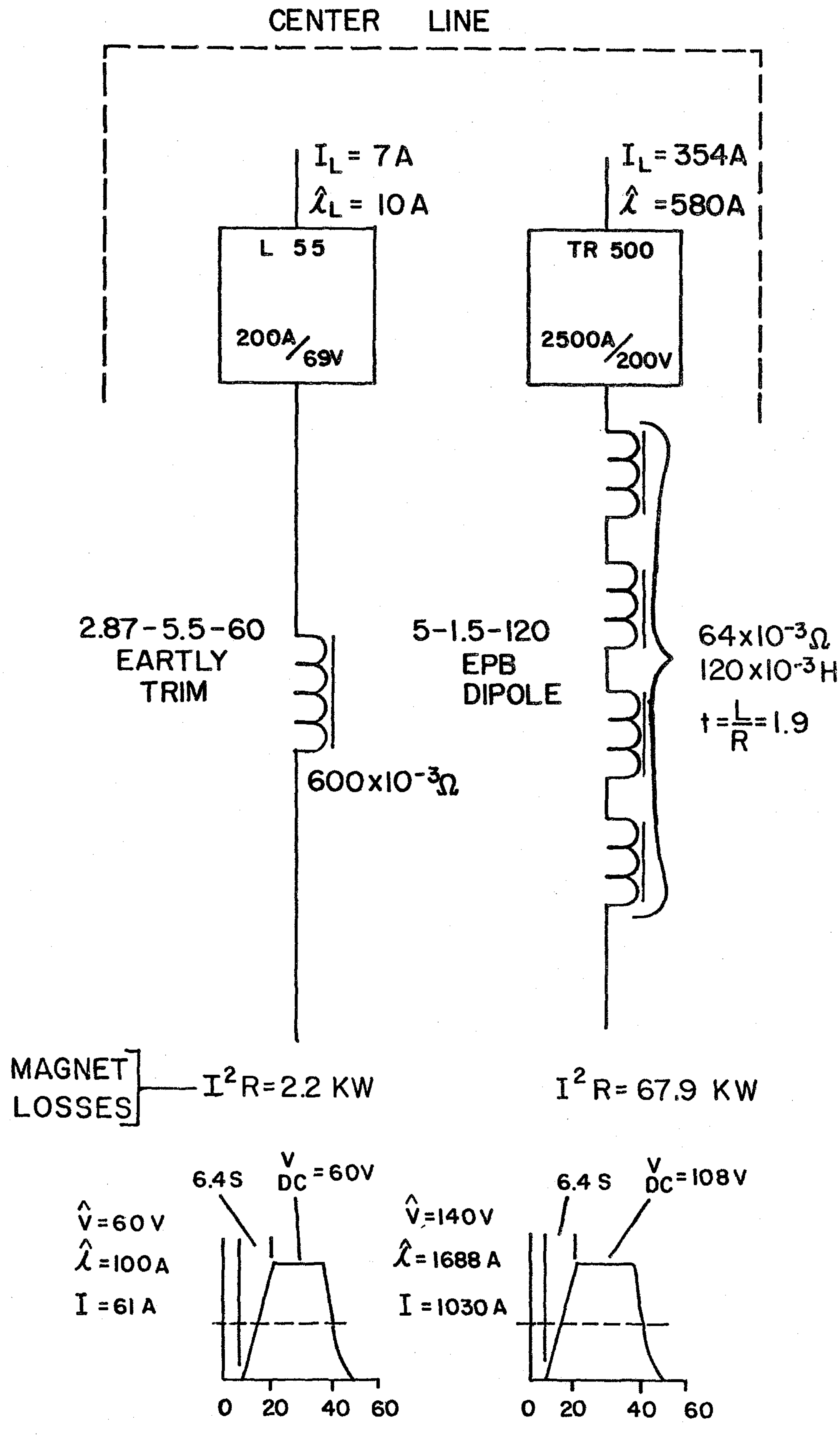

CENTER LINE
I_L = 7A
λ̂_L = 10A
L 55
200A/69V
I_L = 354A
λ̂ = 580A
TR 500
2500A/200V
2.87-5.5-60
EARTLY
TRIM
600x10^-3 Ω
5-1.5-120
EPB
DIPOLE
64x10^-3 Ω
120x10^-3 H
t = L/R = 1.9
MAGNET LOSSES
I^2R = 2.2 KW
I^2R = 67.9 KW
6.4S
V_DC = 60V
V̂ = 60V
λ̂ = 100A
I = 61A
0 20 40 60
6.4 S
V_DC = 108V
V̂ = 140V
λ̂ = 1688 A
I = 1030 A
0 20 40 60

FIGURE 6c

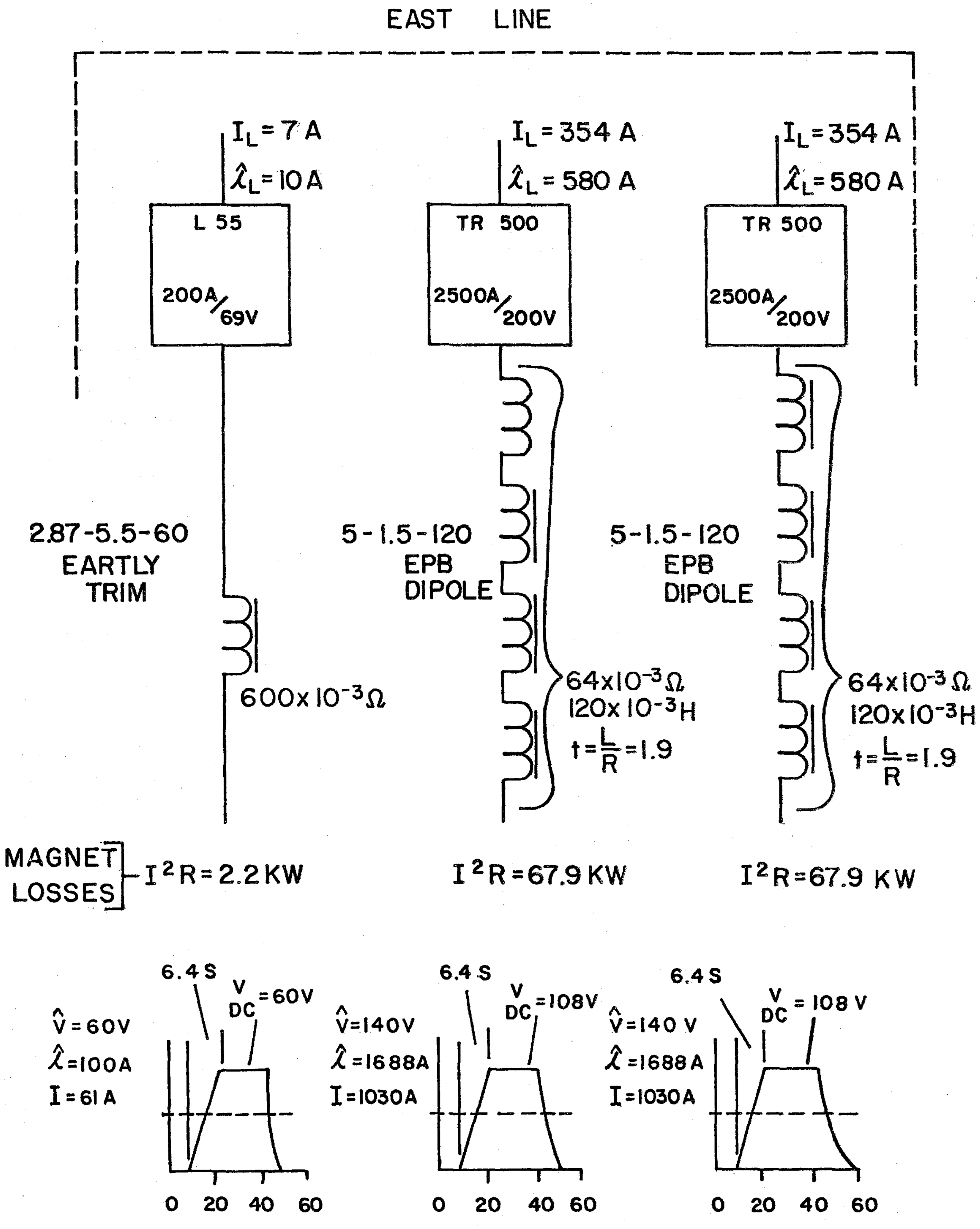

EAST LINE
I_L=7 A
$\hat{\ell}_L$=10 A
L 55
200A/69V
2.87-5.5-60
EARTLY
TRIM
600x10⁻³Ω
I_L=354 A
$\hat{\ell}_L$=580 A
TR 500
2500A/200V
5-1.5-120
EPB
DIPOLE
64x10⁻³Ω
120x10⁻³H
t=L/R=1.9
I_L=354 A
$\hat{\ell}_L$=580 A
TR 500
2500A/200V
5-1.5-120
EPB
DIPOLE
64x10⁻³Ω
120x10⁻³H
t=L/R=1.9
MAGNET LOSSES
I²R=2.2 KW
I²R=67.9 KW
I²R=67.9 KW
6.4 S
V_{DC}=60V
$\hat{V}$=60V
$\hat{\ell}$=100A
I=61 A
0 20 40 60
6.4 S
V_{DC}=108V
$\hat{V}$=140V
$\hat{\ell}$=1688A
I=1030A
0 20 40 60
6.4 S
V_{DC} = 108 V
$\hat{V}$=140 V
$\hat{\ell}$=1688 A
I=1030A
0 20 40 60

FIGURE 6d