Title
MACROSCOPIC QUANTUM EFFECTS IN THE ZERO VOLTAGE STATE OF THE CURRENT BIASED JOSEPHSON JUNCTION

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MACROSCOPIC QUANTUM EFFECTS IN THE ZERO VOLTAGE STATE OF THE CURRENT BIASED JOSEPHSON JUNCTION

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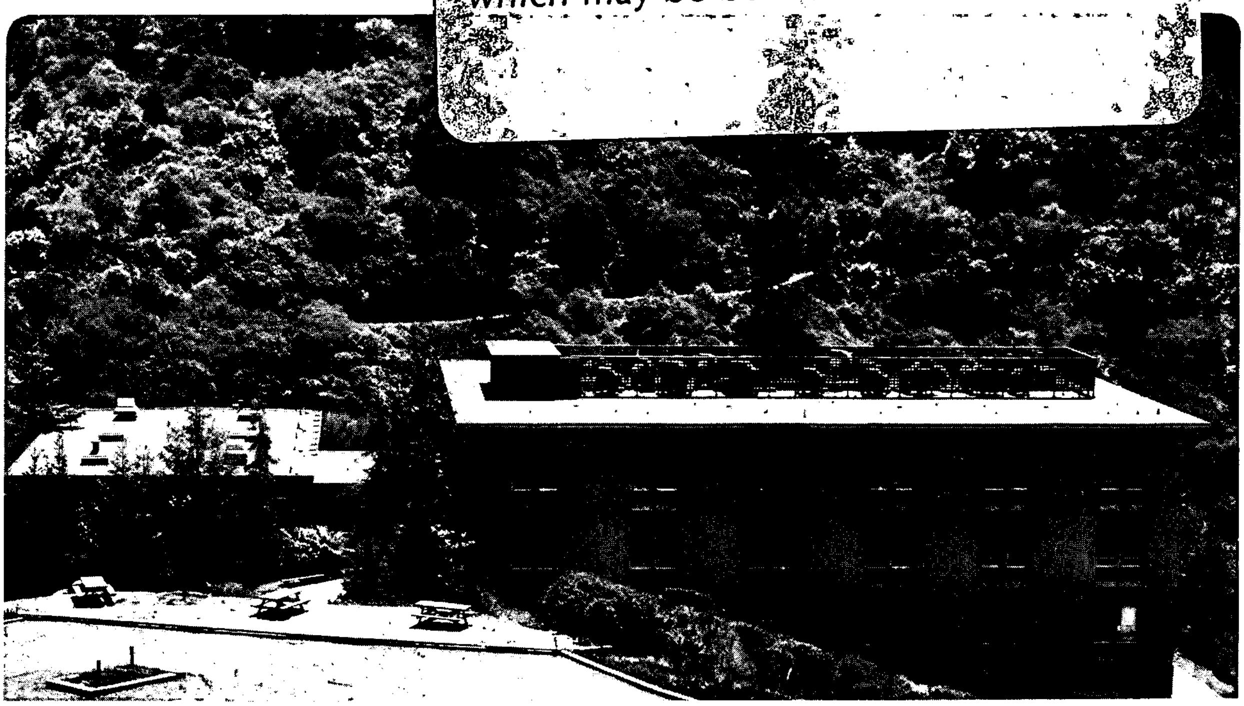
May 1985



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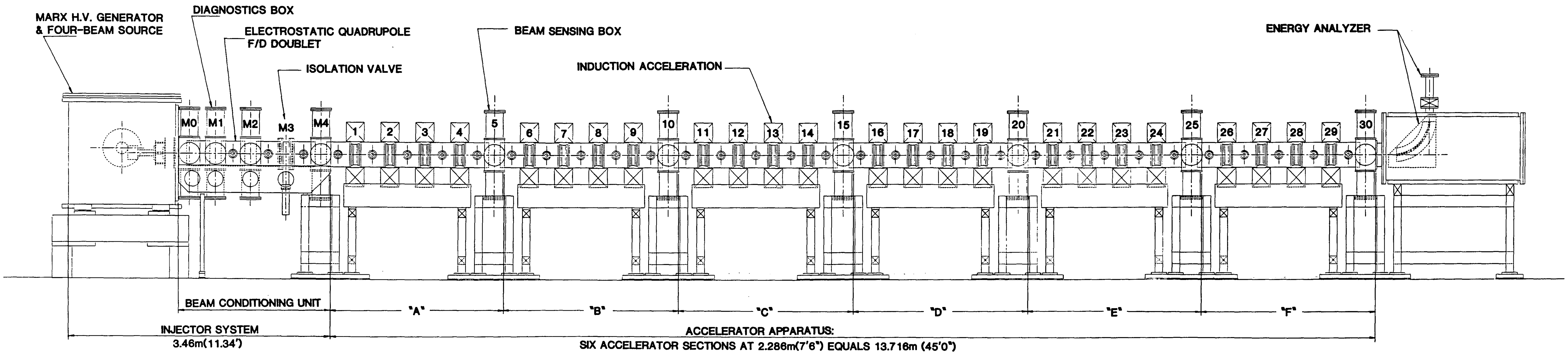

MBE-4 MULTIPLE BEAM EXPERIMENT

FIG. C-4

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D. MBE-4 Injector System

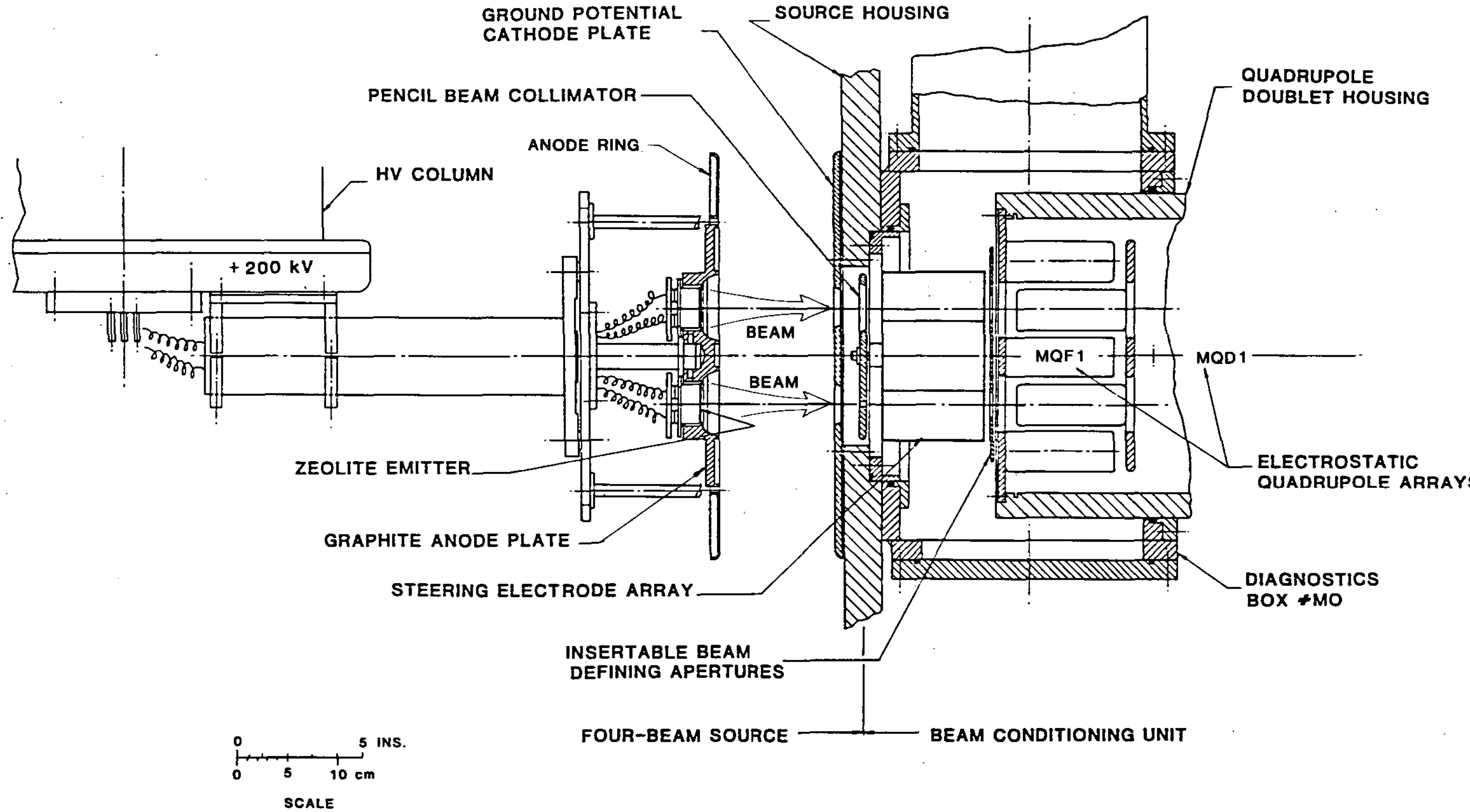
The Injector consists of the existing Marx HV Generator, a Four-beam Source, a Beam Conditioning Unit and the related diagnostic, electronic and vacuum components. These are described in the following subsections.

D1 Marx HV Generator

The existing Marx HV Generator and associated ceramic HV column of the large 1-Ampere Cesium Source[6,7] will now be used for MBE-4. This generator has operated reliably at voltages to 400 kV. For MBE-4, the nominal source voltage will be 200 kV although, for certain experiments, a lower or higher voltage may be used.

D2 Four-Beam Source

The Four-beam Source is shown in Figure D2-1. It is connected to the end of the existing HV column. There is provision for adjusting the position and angle of the source to obtain correct alignment with the MBE-4 axis. The principal parameters of the four-beam source are given in Table D2-1. The source consists basically of four separate emitters of the Zeolite type. Each emitter is set into specially-shaped recesses in the graphite anode to provide focussing. The separate heaters for each emitter are series-connected to the external AC power source. The emitters operate at temperatures of 1000-1200^{o}C in the space-charge-limited mode so accurate control of emitter temperature should not be required.



MBE-4 INJECTOR SYSTEM

FOUR BEAM SOURCE

FIG. D2-1

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TABLE D2-1

MBE-4 INJECTOR FOUR-BEAM SOURCE
PRINCIPAL PARAMETERS

Diode voltage, nominal	200 kV
Diode voltage, range	100-300 kV
Emitter type	Alumino-silicate Zeolite
Emitter diameter	38.1 mm (1.50")
Emitter temperature	1000-1200 C
Emitted ion specie	Cesium +1
Emitted current, nominal at 200 kV	20 mA (before collimation)
Emitted current density at 200 kV	2.0 mA/cm^2
Perveance	4.2×10^{-4}
Beam-to-beam spacing (between axes)	66.68 mm (2.625")

The EGUN program(8) has been used to calculate trajectories of emitted ions such as those shown in Figure D2-2. Each source is not completely symmetrical with respect to its own beam axis because it has three neighboring beams on the "inboard" side while there are no beams on the "outboard" side. Trajectory analyses suggest that only small abberations are present and that azimuthal asymmetries are not significant.

The ground-potential cathode plate is located 133 mm (5.25") from the emitter surfaces and has 38.1 mm (1.50") diameter holes for each of the four beams. As shown in Figure D2-2, the ion beams easily pass through these holes in the cathode plate without beam loss. The cathode plate is water-cooled to absorb heat radiating from the high-temperature Four-beam Source.

Four-beam ion sources have not been built before, so this source is developmental in nature. A single source of the contemplated type has been constructed and tested. Each of the four zeolite emitters will be individually tested in a test stand before installation in the source. As mentioned elsewhere, the Four-beam Source will be installed and tested early in the schedule so that there should be ample time to incorporate modifications should such be required.

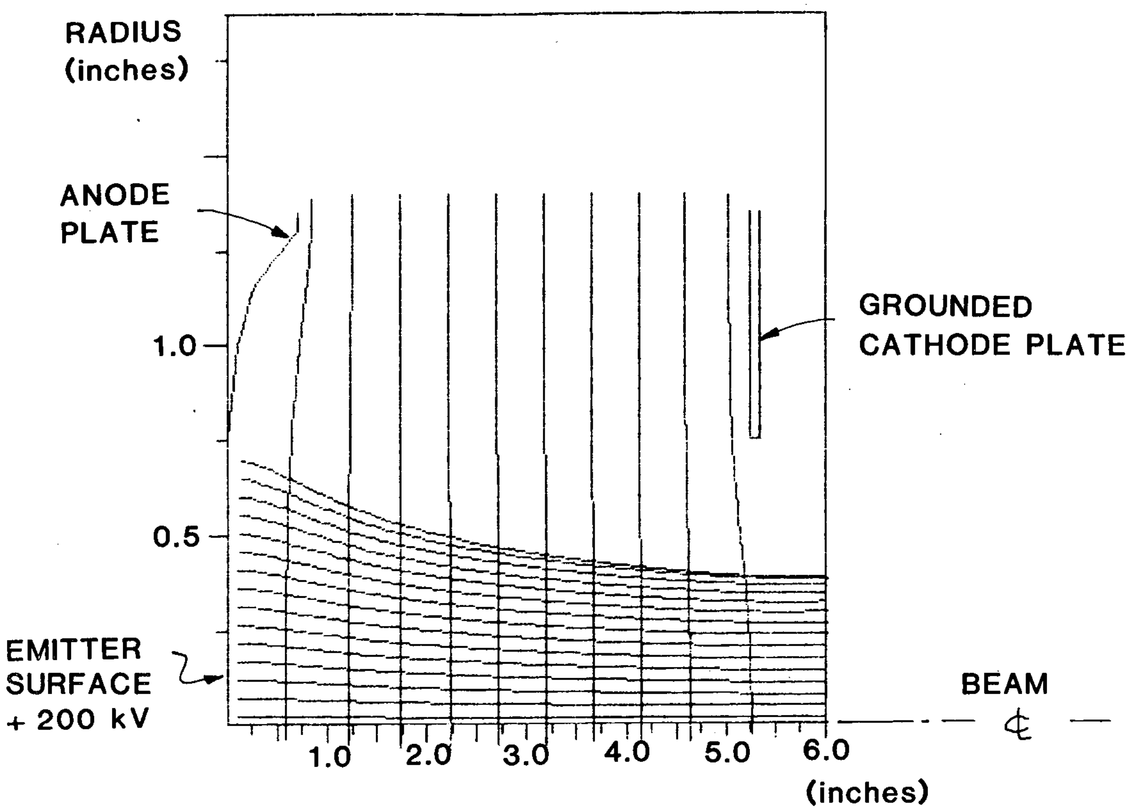

FIG. D2-2

ION TRAJECTORIES FOR ONE OF FOUR CESIUM ION BEAMS

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D3. Beam Conditioning Unit

The Beam Conditioning Unit (sometimes called the matching section) accepts the four ion beams from the Four-beam Source and by appropriate collimation, steering and focussing matches the beams so that they can be delivered in a variety of configurations to the subsequent periodic transport quadrupole arrays in the Accelerator Apparatus. It also contains significant diagnostic capabilities, as given in Table D3-1 and Figure D3-1, which are described more fully later. Thus, the ion beams entering the MBE-4 Accelerator Apparatus are fully characterized. All of the Beam Conditioning Unit components utilize known technologies.

D3.1 Collimating Apertures

A pencil-beam collimator is located just downstream of the cathode plate and immediately upstream of Diagnostic Box #M0, as shown in earlier Figure D2-1. In its normal position, this collimator does not intercept beam. However, when actuated manually, small aperture holes in the collimator disk are rotated into all four beams simultaneously. This forms small low-current pencil-beams for diagnostic purposes.

Beam-defining apertures are located at the exit of Diagnostic Box #M0 and are also shown in earlier Figure D2-1. The 20 mA of total ion current per beam impinges on these apertures, but only the central portion passes through. Initial operation of MBE-4 will utilize 5mA beams obtained by collimating the ~22 mm diameter beam down to ~11 mm (0.42") diameter. For 10 mA beam current, apertures of ~ 15 mm (0.60") diameter will be used. These apertures define the beam position, beam current and beam emittance. The apertures are accurately aligned relative to the MBE-4 axis.

TABLE D3-1

DIAGNOSTIC DEVICES IN BEAM CONDITIONING UNIT

DEVICE	POSITION	PURPOSE
Pencil-Beam Collimator	Box #M0	Reduce space charge loading of beam to measure single-particle effects.
Faraday Cup Array	Box #M4	Measure beam current independently in all four ion beams. (Destructive)
Capacitive Pickup Array	Box #M4	Measure beam current independently in all four ion beams. (Non-destructive)
Emittance sensors, vertical	Box #M4	Horizontal slits to measure vertical emittance of all four ion beams.
Emittance sensors, horizontal	Box #M4	Vertical slits to measure horizontal emittance of all four ion beams.
Harps, vertical (2 total)	Boxes #M1 & M2	Horizontal wire arrays to measure vertical position and height of all four ion beams.
Harps, horizontal (2 total)	Boxes #M1 & M2	Vertical wire arrays to measure horizontal position and width of all four ion beams.

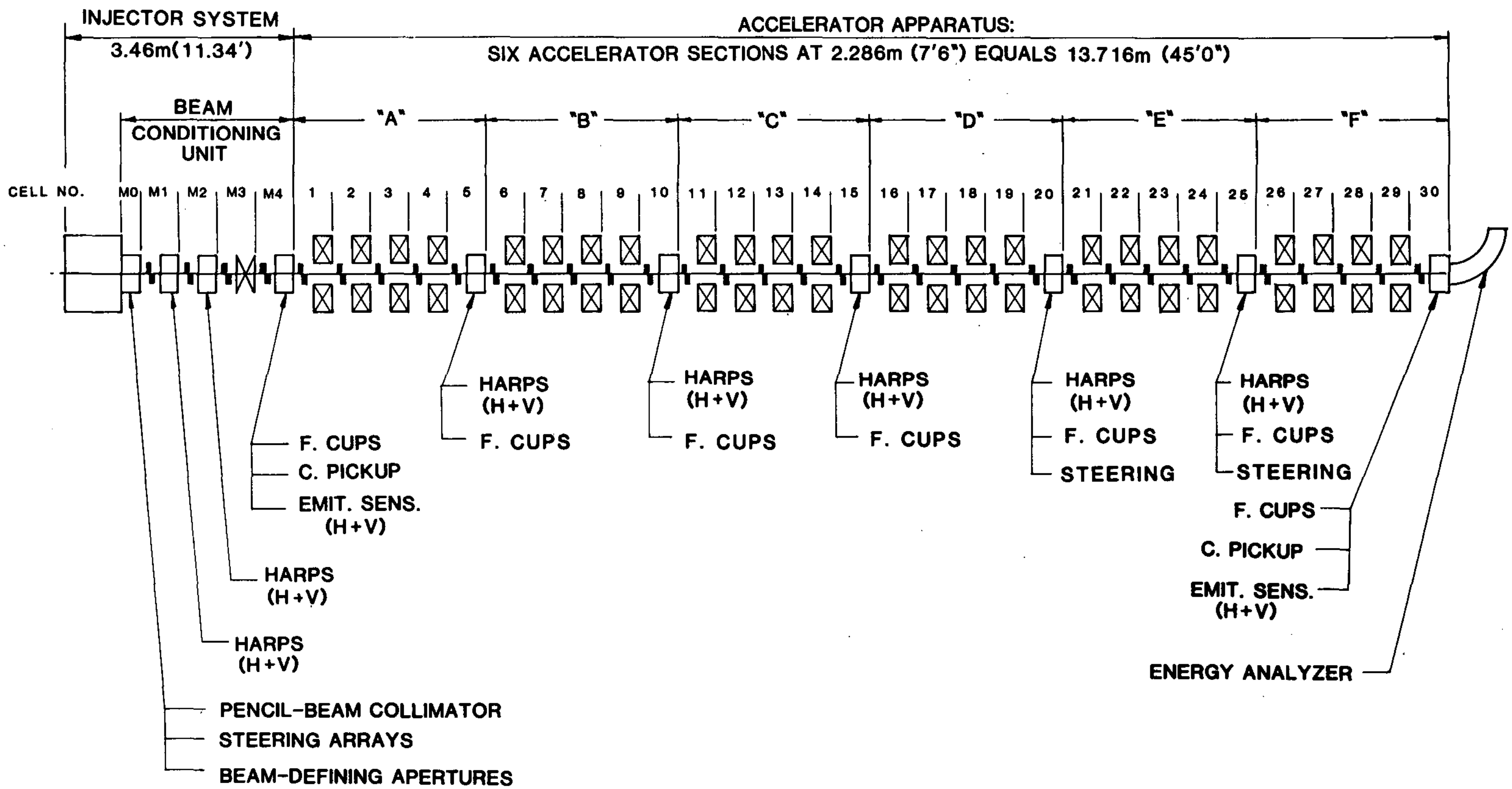

FIG. D3-1

TENTATIVE LOCATIONS OF DIAGNOSTIC DEVICES

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D3.2 Steering Arrays

Electrostatic steering arrays are fixed within Diagnostic Box #MO as shown in earlier Figure D2-1. They provide independent steering of all four beams in both the x and y transverse directions. The configuration of the steering electrodes is shown in Figure D3.2-1. The triangular configuration of each electrode provides a nearly-equal integrated steering impulse independent of beam trajectory through the array. This arrangement has been demonstrated successfully on the Single Beam Transport Experiment (SBTE). A voltage differential of 4 kV total applied between opposing electrodes will provide an angular deflection of 12 mrad to the 200 keV ion beams. Figure D3.2-2 shows the electrical arrangement for powering the steering arrays.

D3.3 Matching Quadrupoles

As mentioned earlier, the heavy ion beams in MBE-4 at full current are subjected to very strong space-charge defocussing forces. In MBE-4, these are counteracted transversely by frequent quadrupole focusing arrays. Because of low ion velocity, the quadrupoles are electrostatic rather than magnetic.

The configuration of the quadrupole arrays for the Beam Conditioning Unit are shown in Figures D3.3-1 and D3.3-2. The beam-to-beam spacing is 66.7 mm (2.625") which is the same as in the Four-beam Source and as was planned for MBE-16. Thus, each of the four beams is coaxial with its respective ion source so no beam offsets are required between the Four-beam Source and the Accelerator Apparatus. The aperture hole for each beam (also the clear distance inside of the quadrupole electrodes) is 54.1 mm (2.128") in diameter which can accommodate beam lateral displacements of at least 15 mm (0.6") without striking the aperture. The quadrupole array consists of round-ended hollow cylindrical electrodes fabricated of aluminum alloy with electroless nickel coating. The diameter of the electrodes is 40.2 mm (1.584") which was selected on the basis of particle simulation computations which included the effects of quadrupole field errors (primarily 12-pole) and of image charges on the focussing electrodes. Each quadrupole array contains nine

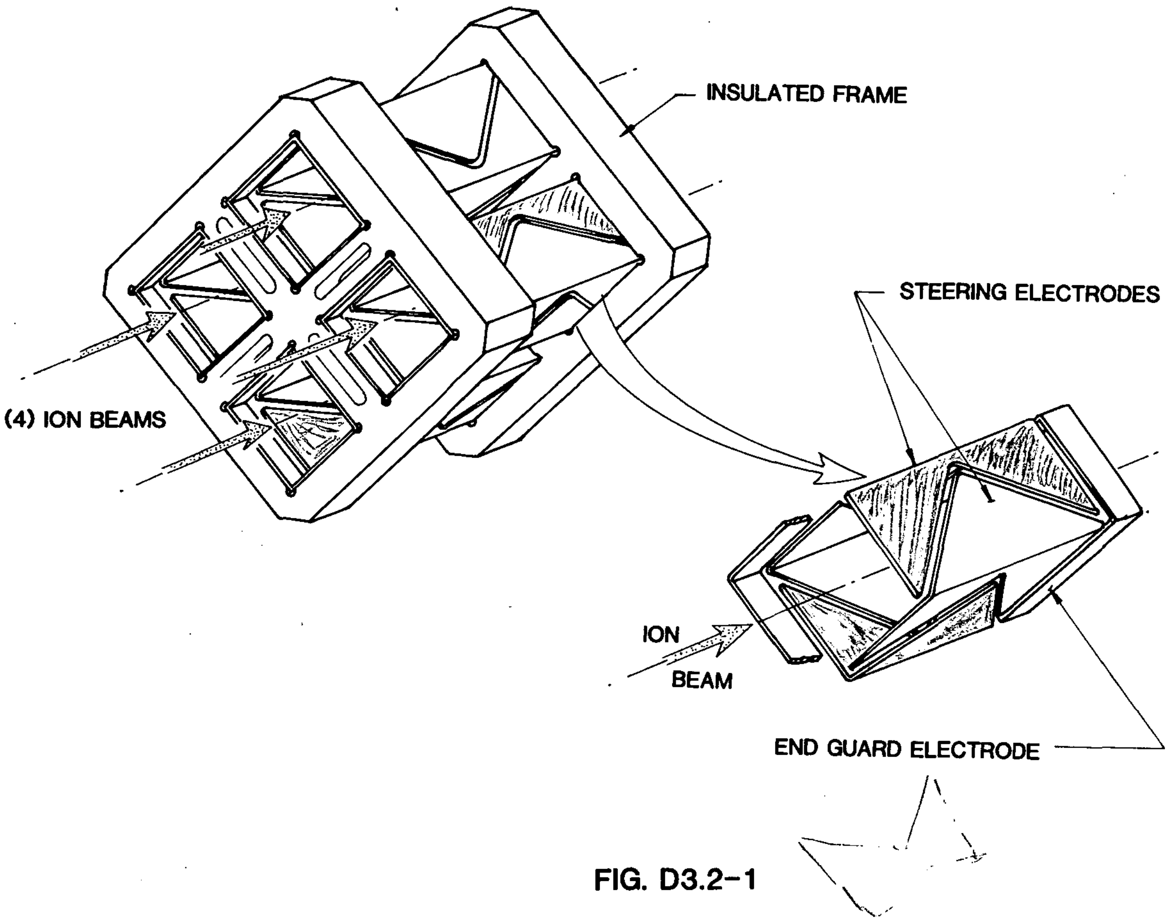
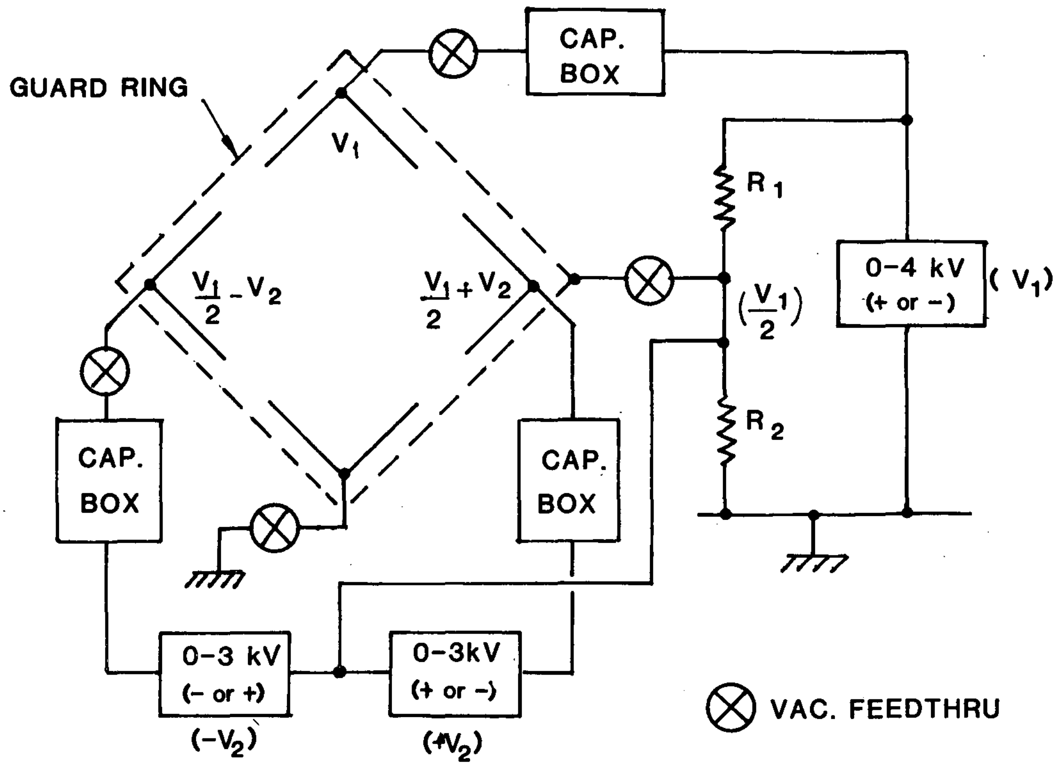


FIG. D3.2-1

ISOMETRIC VIEW OF STEERING ARRAY FOR ION BEAMS

XBL 854-2081

MBE-4 INJECTOR SYSTEM, BEAM CONDITIONING UNIT



CAP. BOX

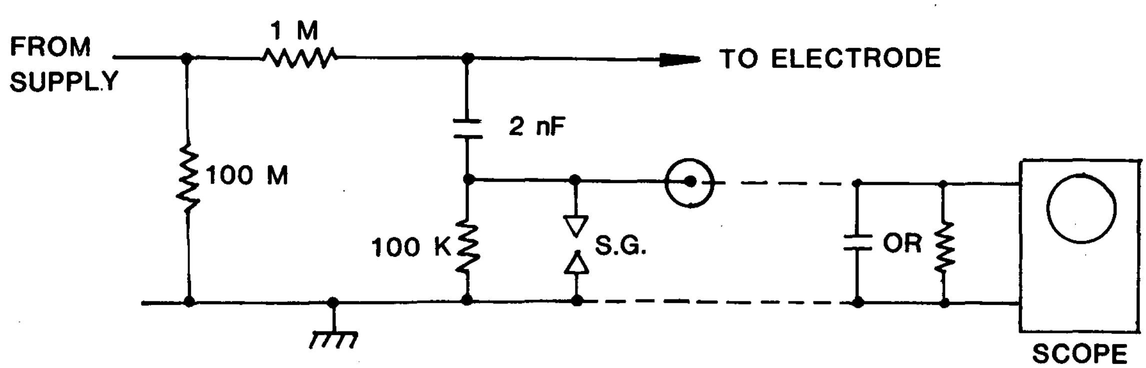


FIG. D3.2-2

STEERING ARRAY ELECTRICAL POWER DIAGRAM
FOR ONE OF FOUR ION BEAMS

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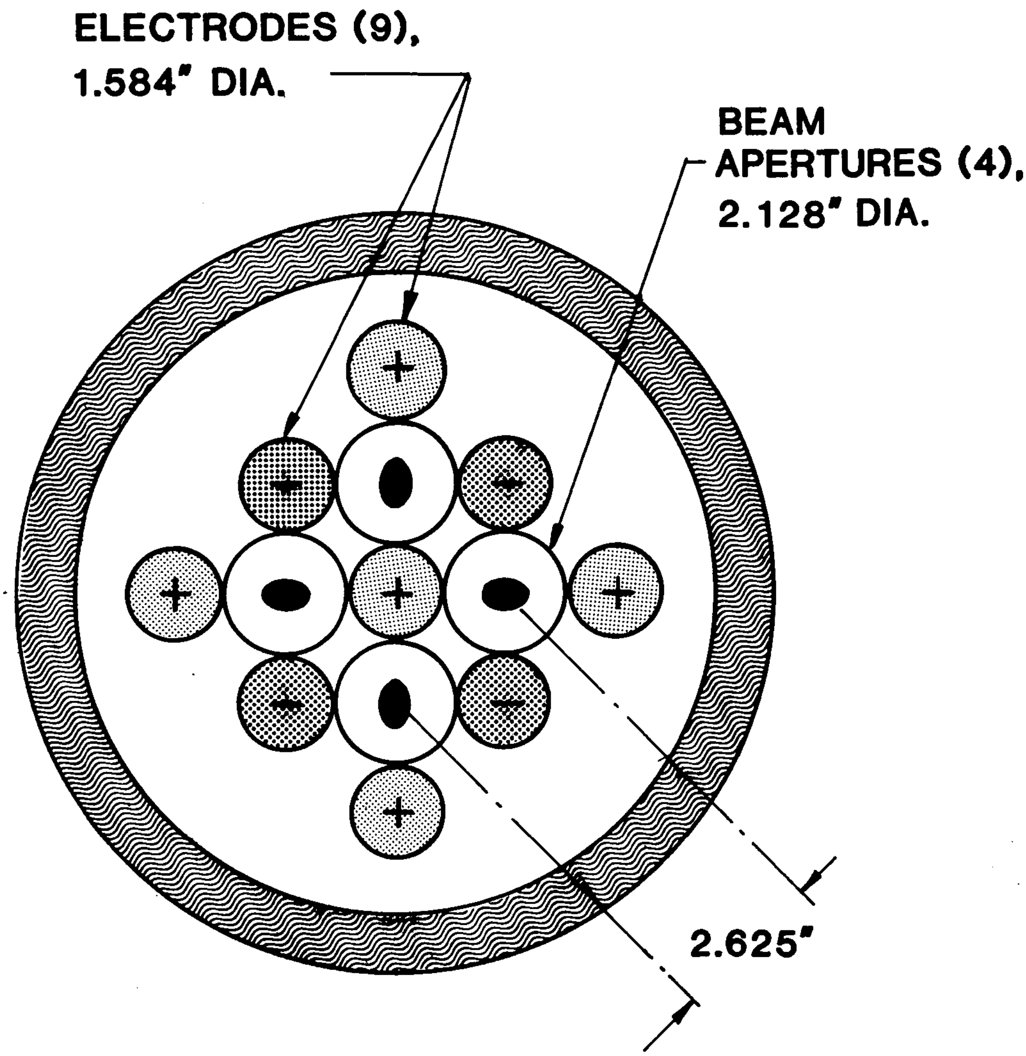

FIG. D3.3-1

TRANSVERSE CROSS-SECTION OF MATCHING QUADRUPOLE ARRAY

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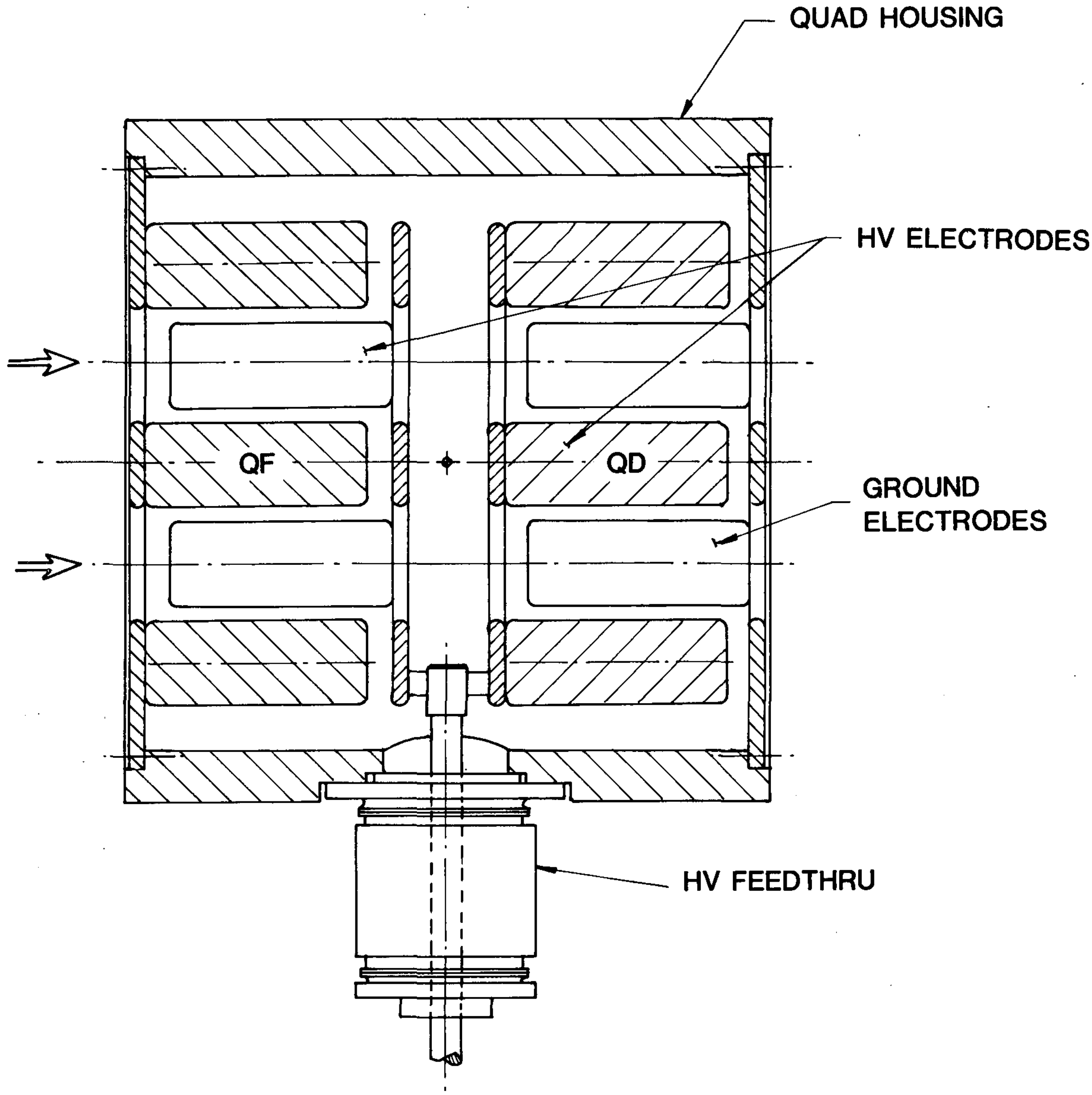

FIG. D3.3-2

LONGITUDINAL CROSS-SECTION OF MATCHING QUADRUPOLE DOUBLET ARRAY

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electrodes. In the "F" quadrupole array, five electrodes are attached to a plate which is electrically grounded while the other four electrodes are attached to a plate which is at negative high voltage. In the "D" quadrupole array this is reversed with four at ground potential and five at negative high voltage. An "F" quadrupole array is defined as one producing horizontal focussing for the two ion beams on the MBE-4 horizontal axis (the "left" and "right" beams looking downstream). It also produces vertical focussing for the two ion beams on the vertical axis (the "top" and "bottom" beams). A "D" quadrupole array produces defocussing in the corresponding ion beams. Ceramic insulators space the high voltage plate from the ground plate. An "F" quadrupole array and a "D" quadrupole array are both mounted to a common quadrupole doublet housing to form a quadrupole doublet unit. All of the foregoing are done with high precision to provide accurate alignment of the electrodes relative to the four beams within 0.1 mm (.004") or less.

In the Beam Conditioning Unit, the four quadrupole doublet housings each have two high-voltage feedthroughs so that separate voltages can be applied to the "F" and "D" quadrupole arrays. Thus, all eight quadrupole arrays in the matching section can be separately powered in order to obtain the desired matching of the ion beams into the Accelerator Apparatus. An example solution of the K-V envelope equations providing a suitable matching is shown in Figure D3.3-3 for 10 mA, 200 keV Cesium ion beams from the source. Table D3.3-1 presents the principal parameters for the matching quadrupoles of the Beam Conditioning Unit.

The focussing quadrupole arrays are each separately powered by an adjustable d.c. supply which can be set at up to 30 kV. A typical arrangement is shown in Figure D3.3-4. Suitable voltage monitoring is provided. Beams passing though the apertures of a quadrupole array will induce some current in the power circuit, tending to change the effective voltage of the array. To minimize this effect, a low impedance capacitive bypass circuit is provided.

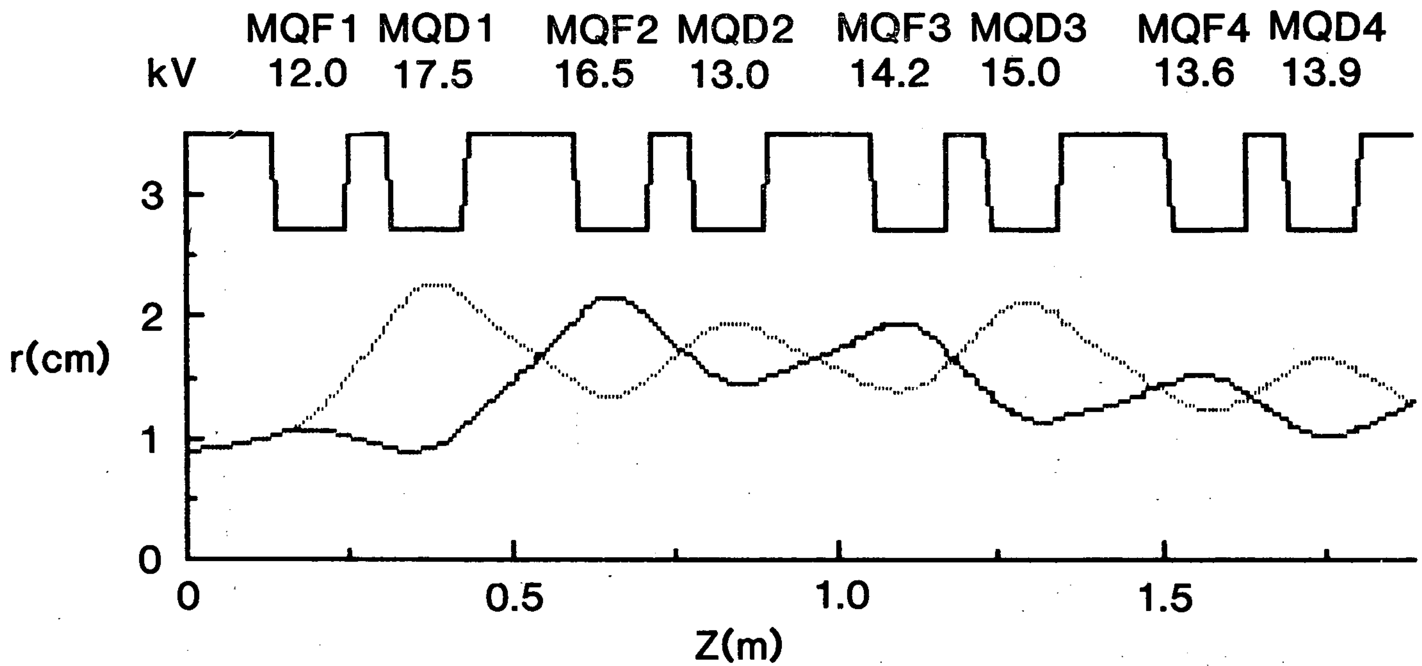

FIG. D3.3-3

AN EXAMPLE OF QUADRUPOLE VOLTAGES PRODUCING SUITABLE MATCHING FROM THE MBE-4 INJECTOR TO THE ACCELERATOR SECTIONS. 10 mA, 200 keV CESIUM ION BEAM HAVING EMITTANCE OF 1.5 x $10^{-7}\pi$ m-rad.

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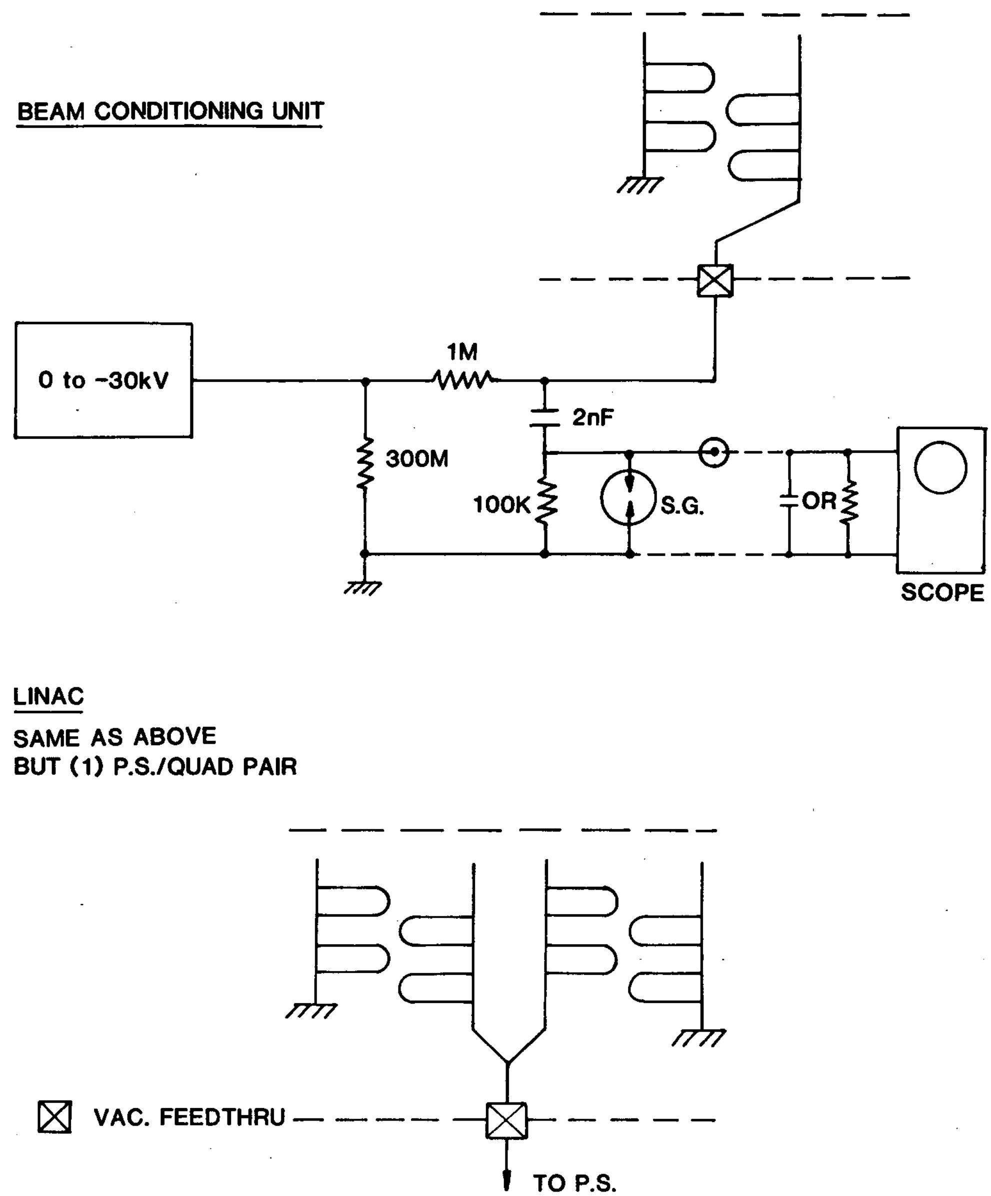

FIG. D3.3-4

POWER SCHEMATIC FOR MBE-4 QUADRUPOLE FOCUSSING SYSTEMS

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Table D3.3-1

Injector System Beam Conditioning Unit
Electrostatic Matching Quadrupole Array Parameters

Beam aperture diameter	54.06 mm (2.128")
Electrode diameter	40.24 mm (1.584")
Beam-to-beam centerline spacing	66.68 mm (2.625")
Electrode length	107.4 mm (4.230")
Electrode end gap	10.2 mm (0.400")
Quadrupole array overall length	134.9 mm (5.310")
Spacing between arrays (clear):	
F to D (mid-doublet)	36.58 mm (1.440")
D to F (diagn. box/accel. gap)	150.9 mm (5.940")
Cell length (one period)	457 mm (18.00")
Applied voltage (electrode-to-electrode)	variable to 30 kV

D3.4 Diagnostic Boxes (Beam Conditioning Unit)

In the Beam Conditioning Unit, vacuum enclosures called "diagnostic boxes" (or just "boxes" for short) connect between adjacent quadrupole doublets. These vacuum enclosures have four ports located at top, bottom, and both sides to accommodate diagnostic devices as well as vacuum system components. All ports are the same size so that devices can be moved to a different port or to a different box as indicated by experimental needs. Unless otherwise noted, all devices can be moved into or out of the beams so that several devices can be located at a given box even though they may not be inserted into the beams simultaneously. Also, unless noted, the devices are moved manually by precision ball-screw drives of the type used successfully on SBTE. In the Beam Conditioning Unit, there are four diagnostic boxes labeled #M0, #M1, #M2 and #M4. Box #M0 differs from the remainder because of its proximity to the four-beam source. An isolation valve replaces Box #M3. An example of installed diagnostic devices is shown in Figure D3.4-1 where four devices (Faraday Cup Array, Capacitive Pickup Arrays, V emittance and H emittance sensors) are accommodated in Diagnostic Box #M4.

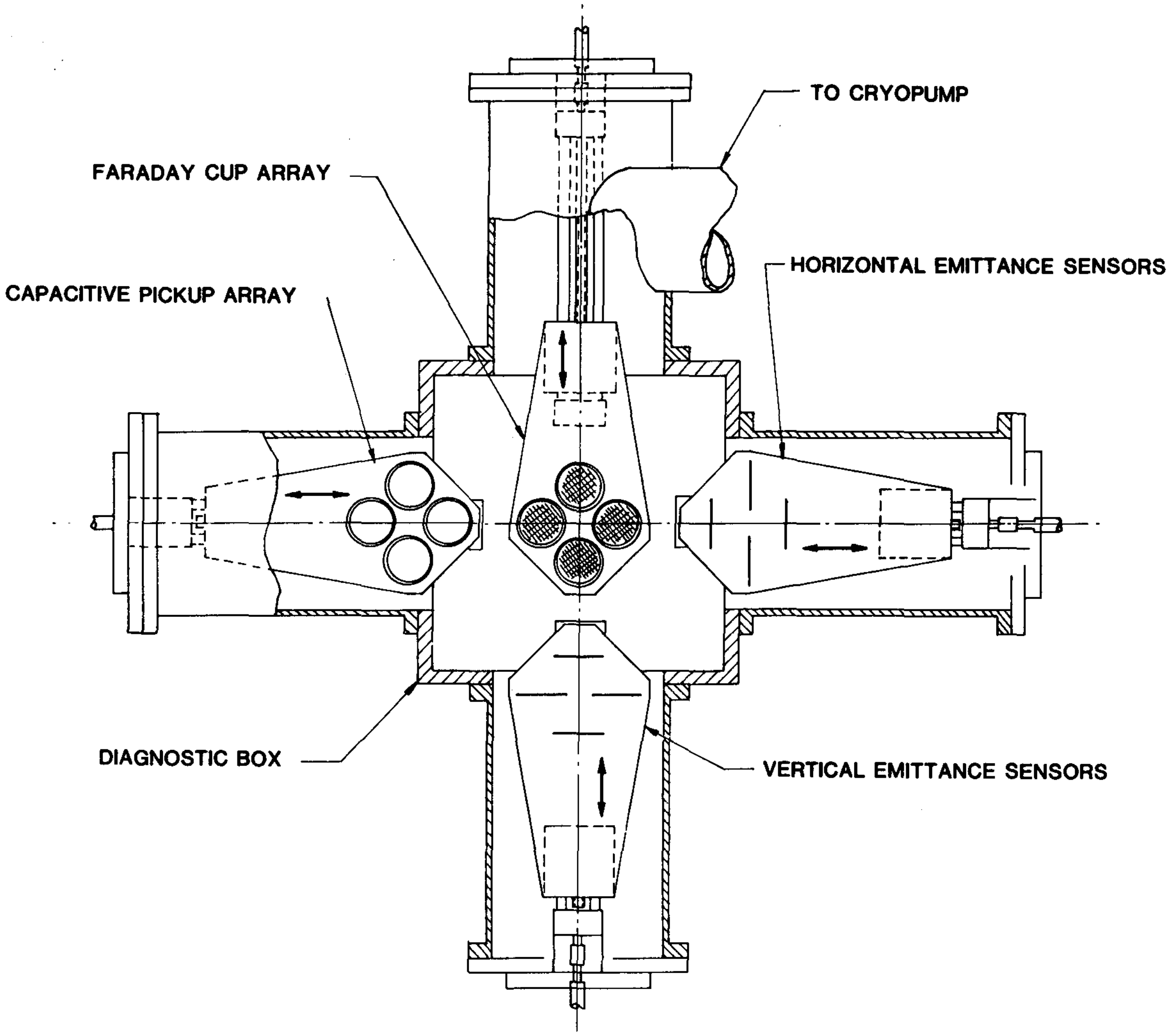

FIG D3.4-1

TRANSVERSE CROSS-SECTION (LOOKING UPSTREAM) OF DIAGNOSTIC BOX #M4 WITH FOUR DIAGNOSTIC DEVICES INSTALLED.

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D3.5 Faraday Cup Array (Beam Conditioning Unit)

The Faraday Cup Array configuration is shown in Figure D3.5-1. It consists of four Faraday cups, each with a bias guard ring to suppress secondary electron emission which would jeopardize the proper measurement of the intercepted ion beam current. This type of cup has been used successfully on SBTE . The electrical measurement circuitry for the Faraday cups is shown in Figure D3.5-2.

D3.6 Capacitive Pickup Array (Beam Conditioning Unit)

The Capacitive Pickup Array configuration is shown in Figure D3.6-1. This array, sometimes called a charge monitor, senses the capacitive charge induced as the four ion beams pass through their respective pickup electrodes. The beams pass through this array without beam loss, which is not true for the Faraday Cup Arrays. If these Capacitive Pickup Arrays prove as useful as is anticipated, the Faraday Cup Arrays will likely be replaced by these or perhaps by Capacitive Pickup Arrays similar in arrangement to the steering arrays so that beam position can be detected as well as beam current. The electrical circuit for the Capacitive Pickup Array is shown in Figure D3.5-2 also.

D3.7 Emittance Sensors (Beam Conditioning Unit)

An Emittance Sensor array is shown in Figure D3.7-1 which is suitable for measuring emittance in one plane (e.g. vertical or horizontal). It consists of an upstream plate with four narrow slits (one for each beam) and of a downstream plate with four narrow slits but also with beam current collectors behind the downstream slits. The plates are approximately 120 mm (4.8") apart axially. The upstream and downstream slit sizes are 0.010" and 0.005" respectively. The two slit plates can each be precisely and independently driven by their own external stepping motors. In use, the upstream slit plate is set at one position while the downstream slit plate is scanned to obtain angular divergence. This process is repeated at successive upstream positions to obtain the beam emittance. One array with horizontal slits is used to sense vertical

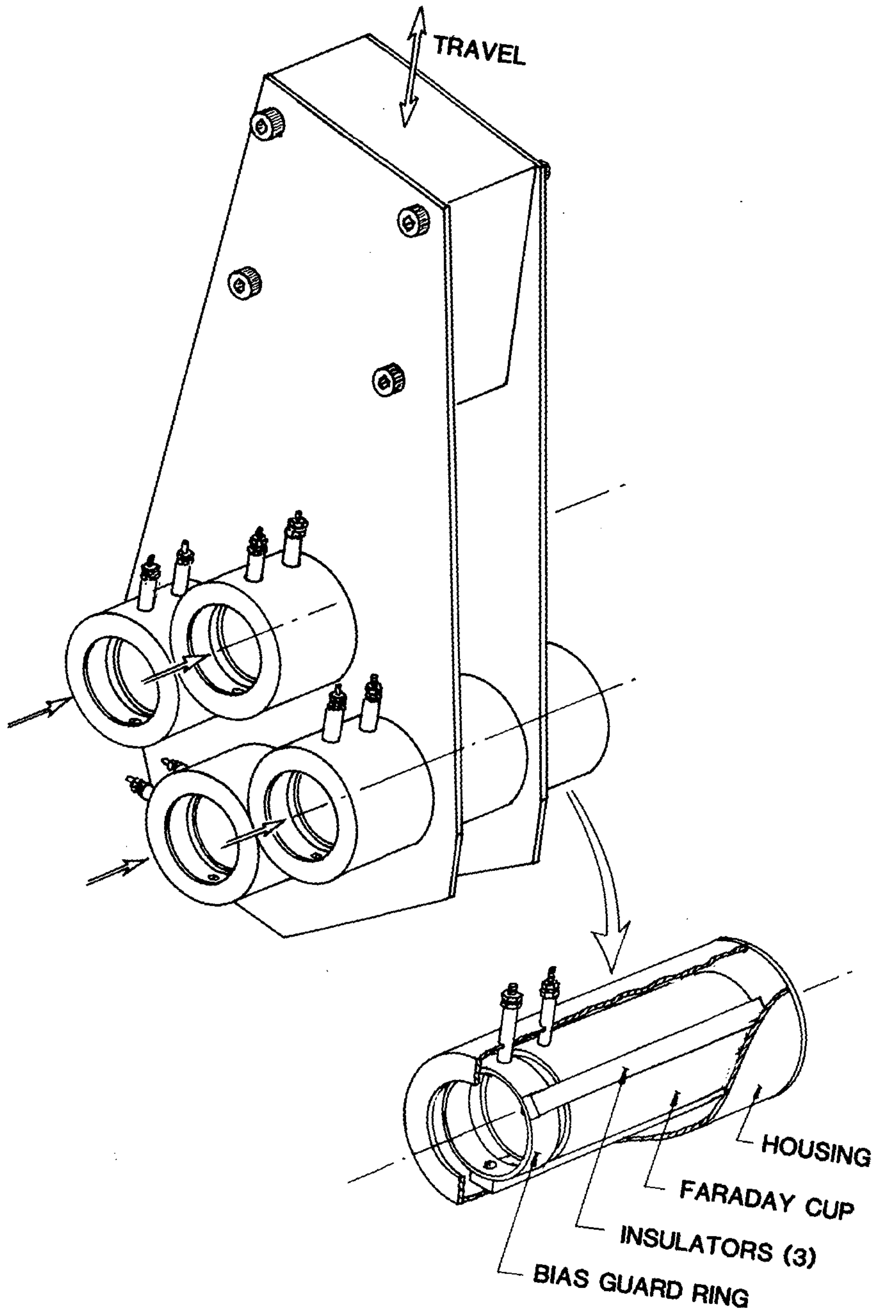

FIG. D3.5-1
CONFIGURATION OF FARADAY CUP ARRAY

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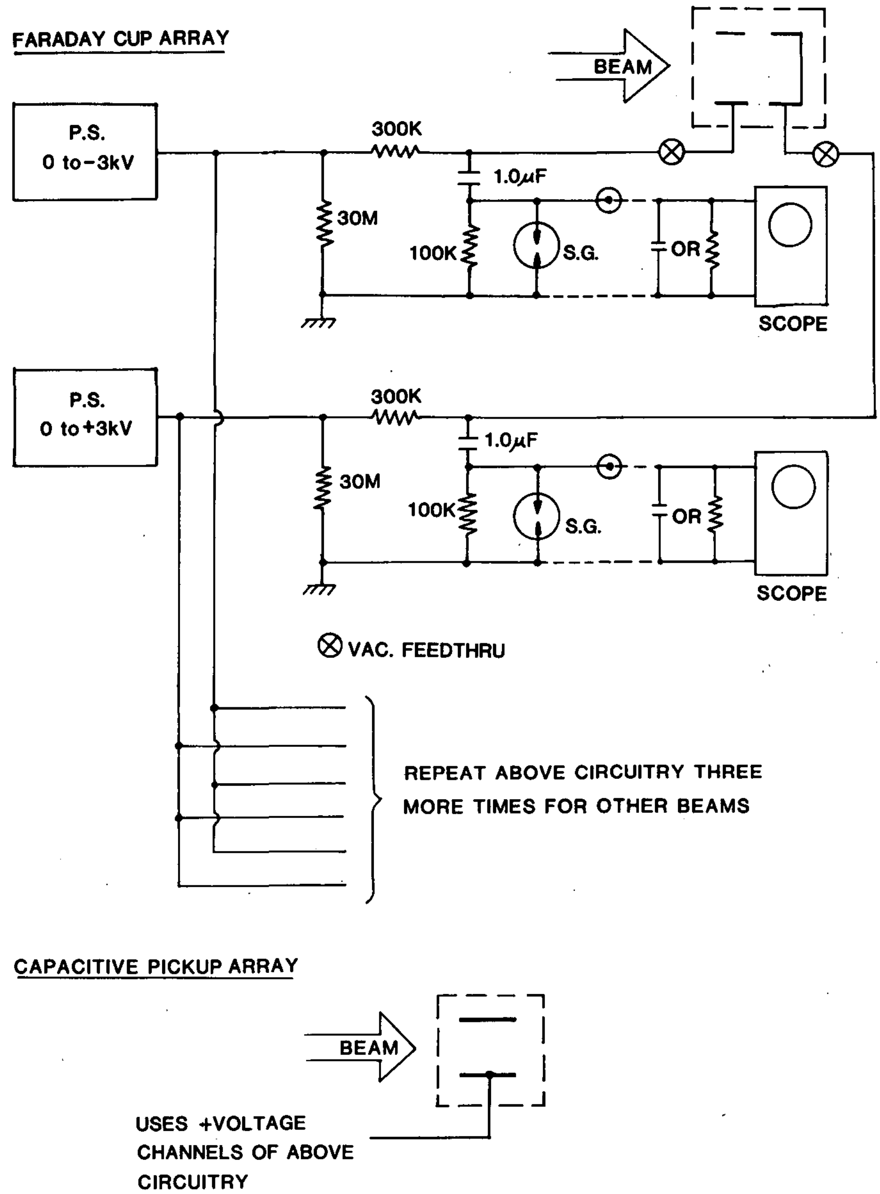

FIG. D3.5-2

ELECTRICAL CIRCUIT FOR FARADAY CUP ARRAY
AND CAPACITIVE PICKUP ARRAY

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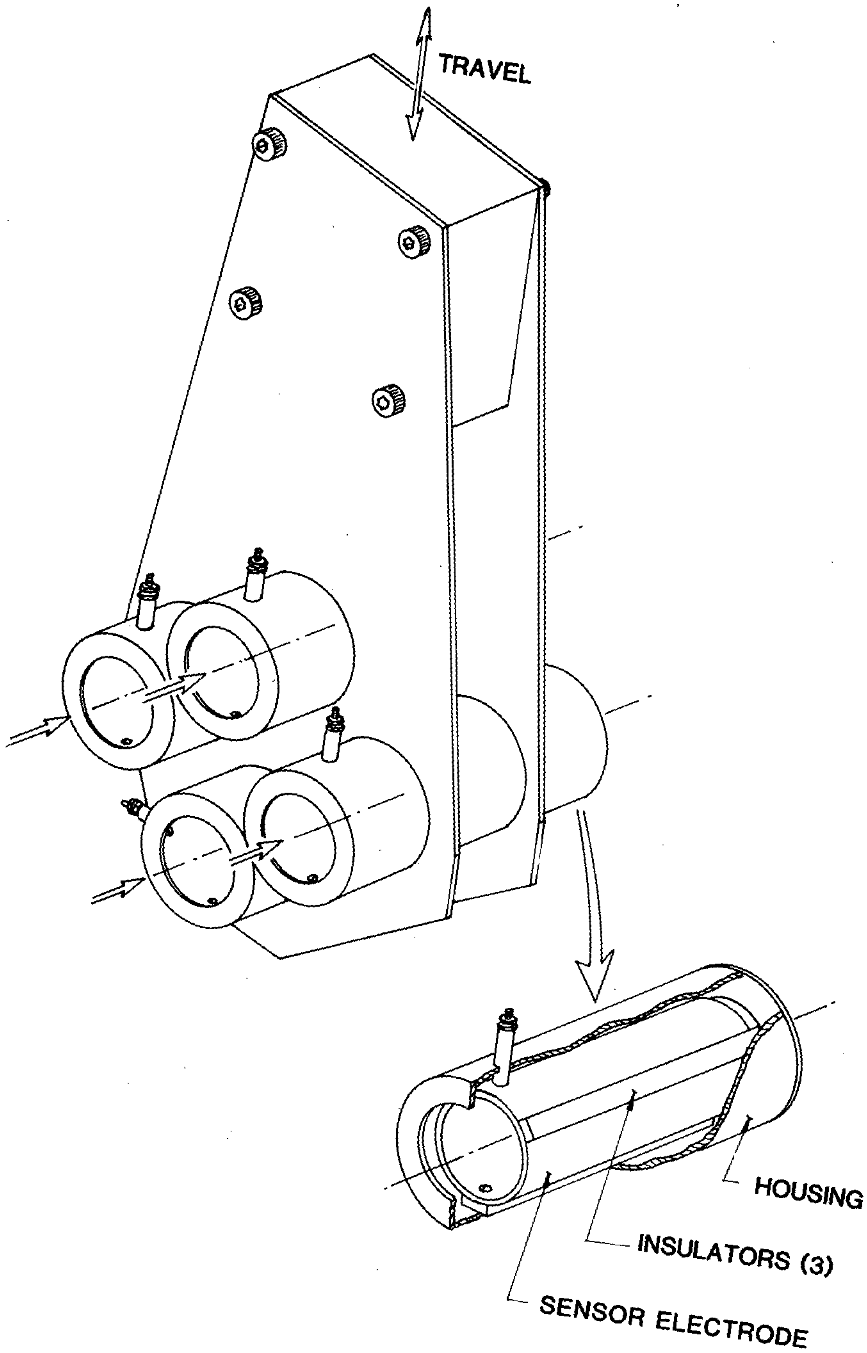

FIG. D3.6-1
CONFIGURATION OF CAPACITIVE PICKUP ARRAY

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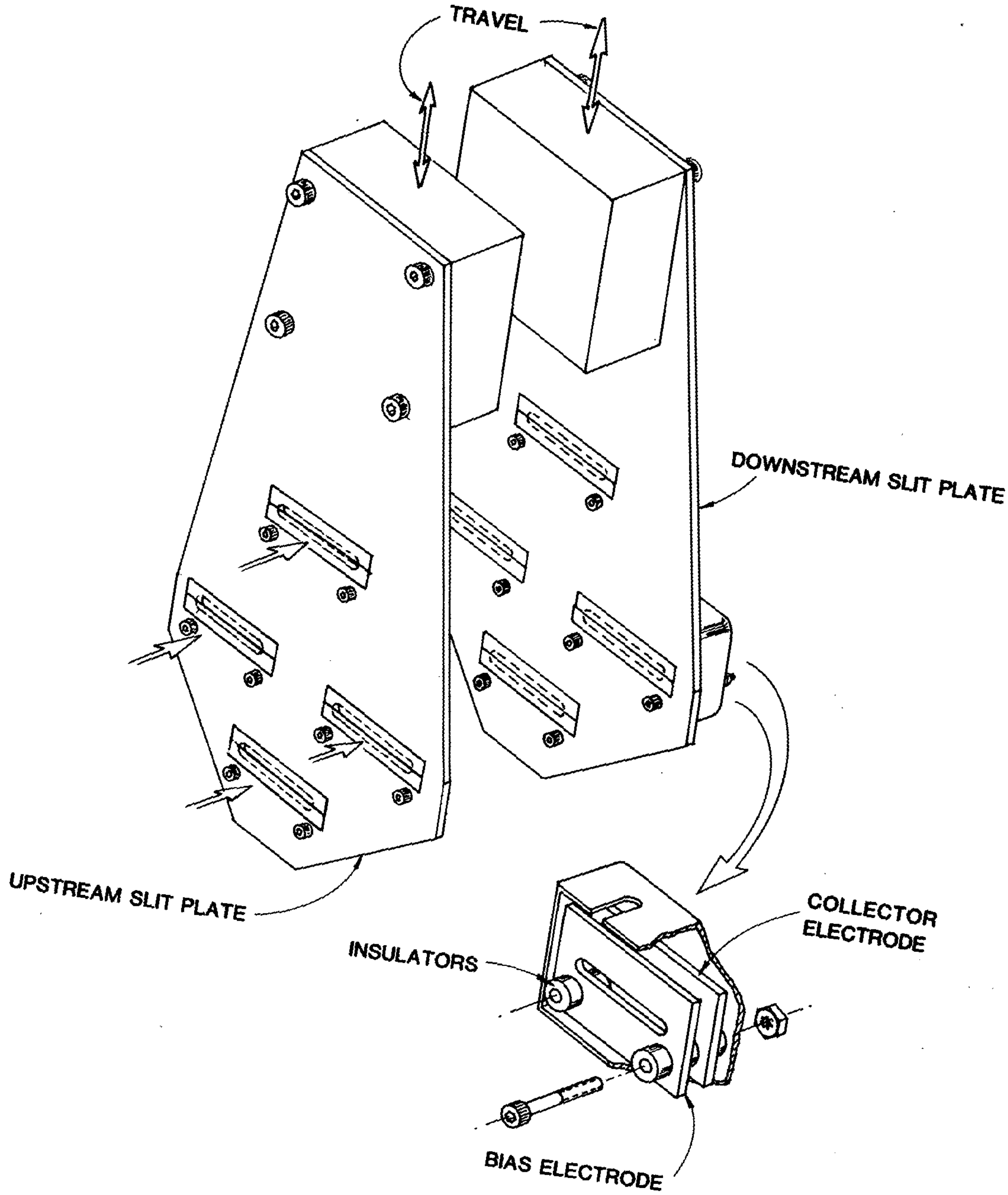

FIG. D3.7-1
CONFIGURATION OF AN EMITTANCE SENSOR ARRAY FOR MEASURING EMITTANCE IN ONE PLANE.

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emittance while a separate array with vertical slits is used to measure horizontal emittance. This arrangement has worked successfully for a single ion beam on SBTE. An additional feature is that the upstream vertical slit can be used in conjunction with the upstream horizontal slit to create the equivalent of a pinhole aperture that can be scanned over the beam cross-section to assess local current densities within the beam. The electrical circuitry for the emittance sensors is shown schematically in Figure D3.7-2.

D3.8 Harps (Beam Conditioning Unit)

An array of parallel wires, called a harp, will be used to sense the transverse size and position of each beam. Each harp consists of 0.010" tungsten wires on 0.050" centers. Harps for four beams are mounted onto a common frame which can be inserted simultaneously into all four beams. One array of four harps with horizontal wires is used to measure the beams vertically while a separate array of four harps with vertical wires is used to measure the beams horizontally. Harps also have proven effective on SBTE. The wires are flexibly connected to feedthroughs at the vacuum wall. The electrical circuitry for the harps is shown in Figure D3.8-1.

D3.9 Support and Alignment (Beam Conditioning Unit)

The elements of the Beam Conditioning Unit are mounted onto a support girder structure which resembles a lathe bed. Diagnostics Boxes #M0, M1, M2 and M4 will be accurately positioned by shims on the support girder. Quadrupole doublets MQF1/MQD1, MQF2/MQD2, MQF3/MQD3 and MQF4/MQD4 are accurately keyed to the end openings of the Diagnostic Boxes. A precision electronic level establishes the correct rotational position about the MBE-4 axis. A special surveying fixture that indexes to either end of a quadrupole doublet and another fixture that indexes to the end openings in the Diagnostic Boxes will be used to assure correct alignment within 0.1 mm (0.004") or less. The support girder, in turn, is mounted and aligned to a support stand at both ends in a manner so that the whole girder with all of its equipment can be realigned as a unit, if needed. The support stands rigidly support the components and are strong enough to resist a major earthquake, should such occur.

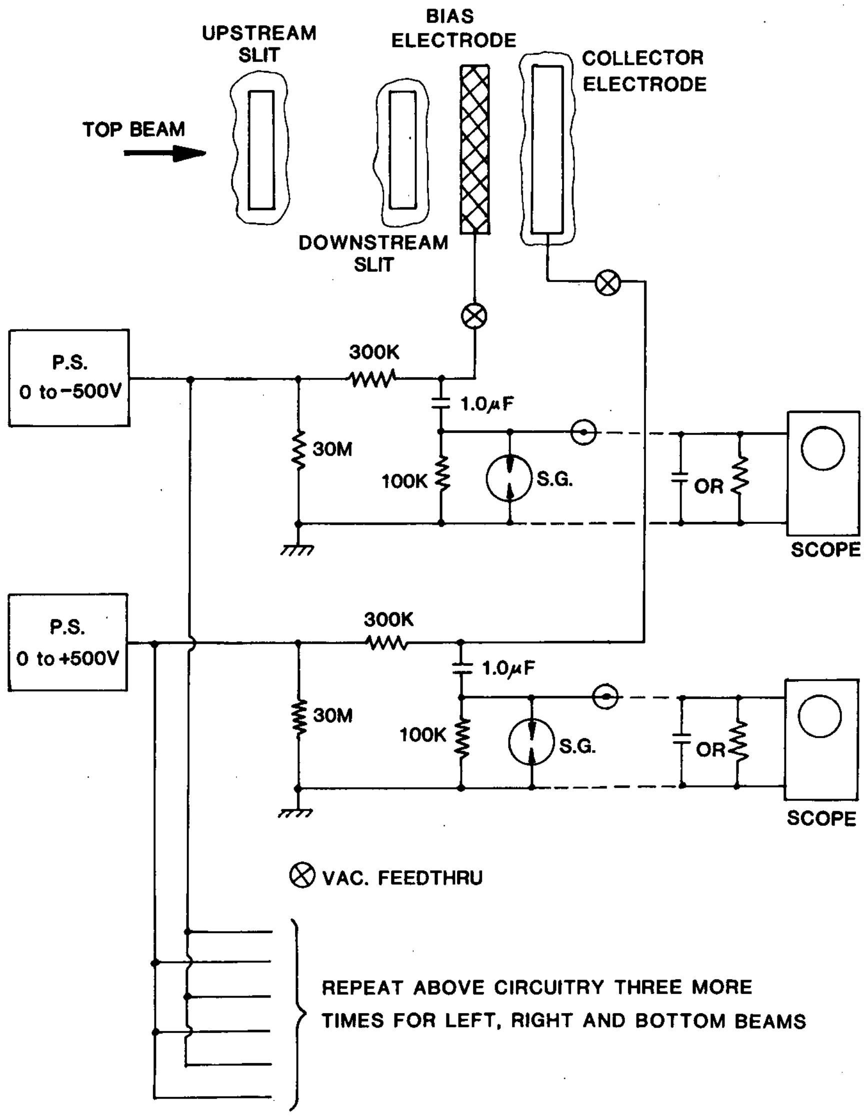

FIG. D3.7-2
ELECTRICAL CIRCUIT FOR AN EMITTANCE SENSOR ARRAY

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MBE-4 HARPS

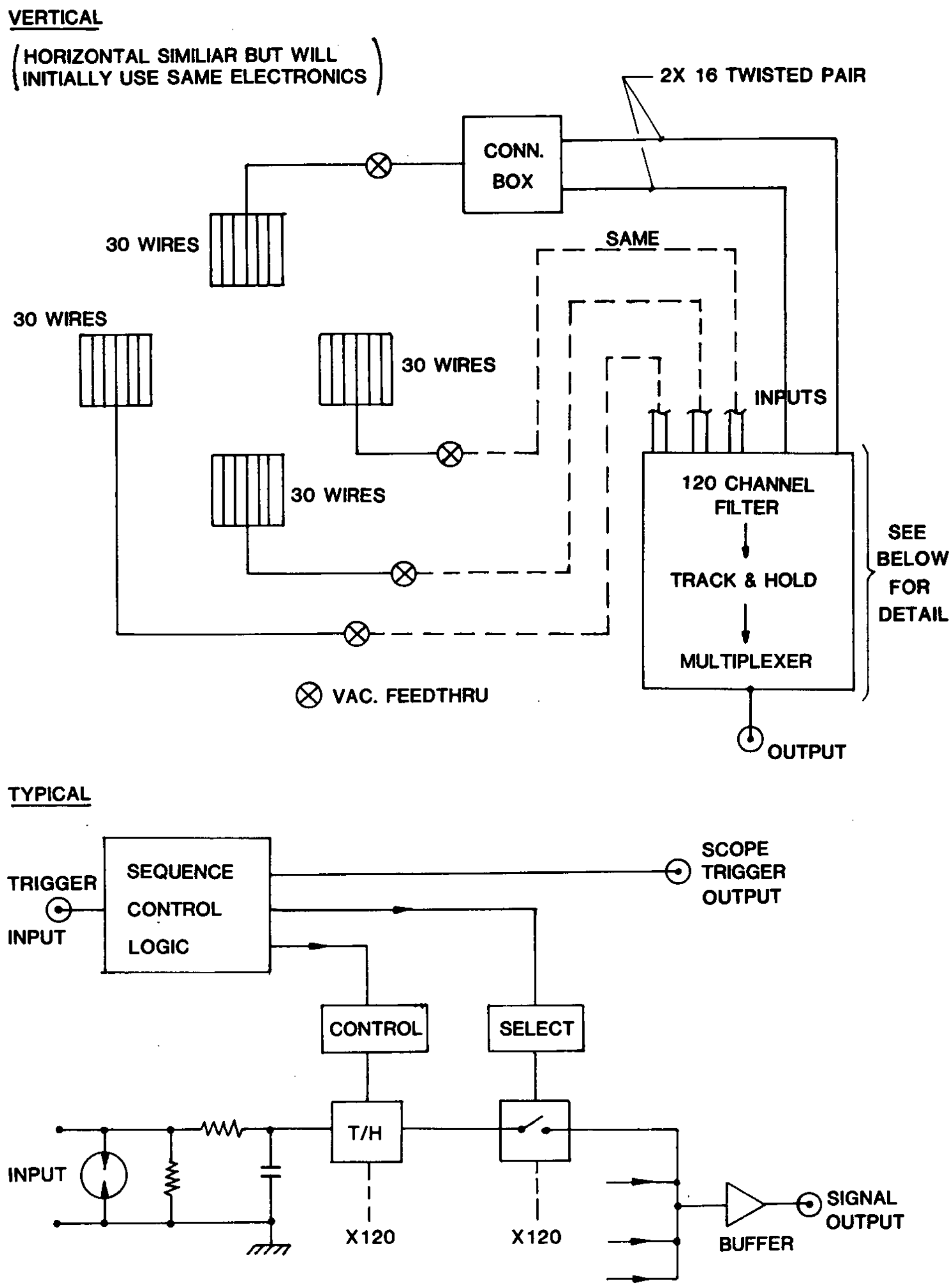

FIG. D3.8-1

ELECTRICAL CIRCUIT SCHEMATIC FOR THE HARPS

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D4 Vacuum System (Injector System)

The vacuum housing for the Four-beam Source is the one from the 1-Ampere large Cesium Source except that the beams are extracted at 90° to the former direction which required modification of the coverplates. The vacuum housing for the Beam Conditioning Unit consists of the quadrupole doublet housings plus the diagnostic boxes. Vacuum joints are sealed with Viton gaskets. A 10-inch Viton-sealed gate valve occupies the position of Diagnostic Box #M3 to permit isolation of the Injector and upstream portion of the Beam Conditioning Unit from the remainder of MBE-4.

The vacuum pumping arrangement is shown schematically in Figure D4-1. The source housing is pumped by two existing turbo-molecular pumps backed by a single mechanical pump. Experience has shown that this amount of pumping should achieve a pressure in the upper 10^{-7} Torr range. Diagnostic Box #M0 is relatively isolated vacuum-wise from the source housing because the apertures for the four beams provide only a modest vacuum conductance. The Beam Conditioning Unit is pumped by cryopumps located at Boxes #M0 , #M2 and #M4. This should result in a pressure of less than 3×10^{-7} Torr for much of the Unit. An additional pump can be added at Box #M1, if needed. Valves are located for regeneration of the cryopumps and for roughing of the vacuum system. Ionization and thermocouple vacuum guages are located appropriately to monitor pressures.

D5 Control and Monitoring (Injector System)

A stand-alone control and monitoring arrangement will be used for the Injector System. Existing components of the Marx HV Generator will be incorporated. Most of the equipment will be located in the electronics racks adjacent to the Injector System. The control and monitoring will be compatible with the subsequent equipment for the Accelerator Apparatus and, where feasible, will be compatible with upgrading to a computerized system..

D6 Installation (Injector System)

The Injector System will be installed in phases. Phase 1A will permit initial testing of the new Four-beam Source at an early time so that modifications, if any, can be accommodated without jeopardizing the subsequent

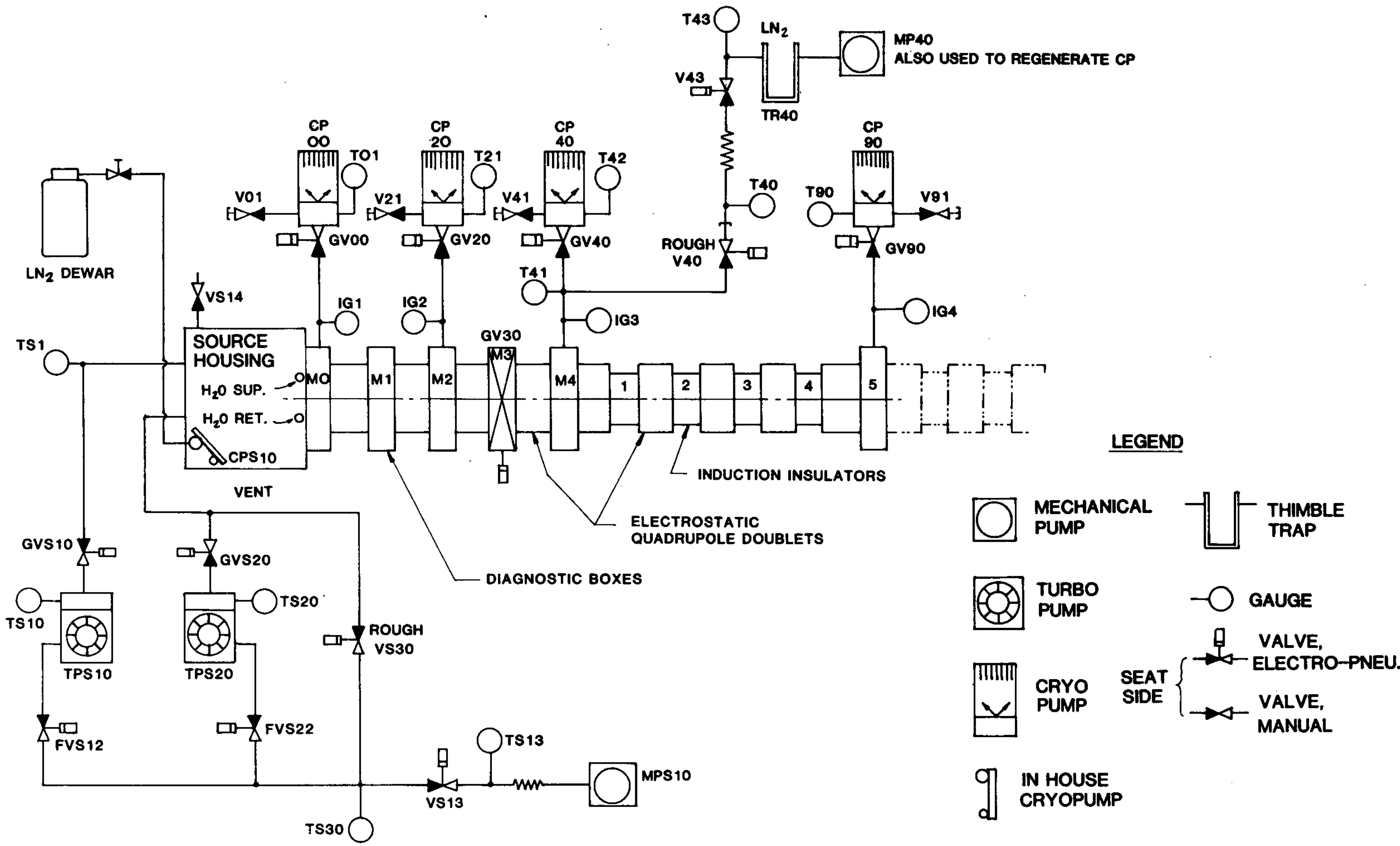

FIG. D4-1

MBE-4

VACUUM SCHEMATIC

INJECTOR SYSTEM & FIRST ACCELERATOR SECTION

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MBE-4 experimental program. The Phase 1A configuration is shown in Figure D6-1. It comprises the Marx HV Generator, the Four-beam Source and Diagnostic Box #M0. The steering array in Box #M0 is removed temporarily to accommodate a Faraday Cup Array, a Capacitive Pickup Array and Emittance Sensors, both vertical and horizontal. These will permit monitoring of the current, size and emittance of the four ion beams.

The configuration for Phase 1B is shown in Figure D6-2. The vacuum system will be extended to include a quadrupole doublet housing plus Diagnostic Box #M1. The Faraday Cup Array, the Capacitive Pickup Array and the emittance sensors (V+H) will be moved from Box #M0 to Box #M1. The Steering Arrays and the Collimating Apertures will be placed in Box #M0. These will permit generation and characterization of ion beams that are steered and collimated.

Phase 1C completes the installation of the Injector System, including the balance of the Beam Conditioning Unit components. The Beam Conditioning Unit components will be precisely aligned to the MBE-4 centerline and to the Four-beam Source. This arrangement will permit a full characterization of the Injector System and its Four-beam Source at a relatively early stage of the construction of the MBE-4 experiment so that modifications to the Injector System, if any, should not jeopardize the installation and testing of the downstream Accelerator Apparatus and the subsequent MBE-4 experimental program.

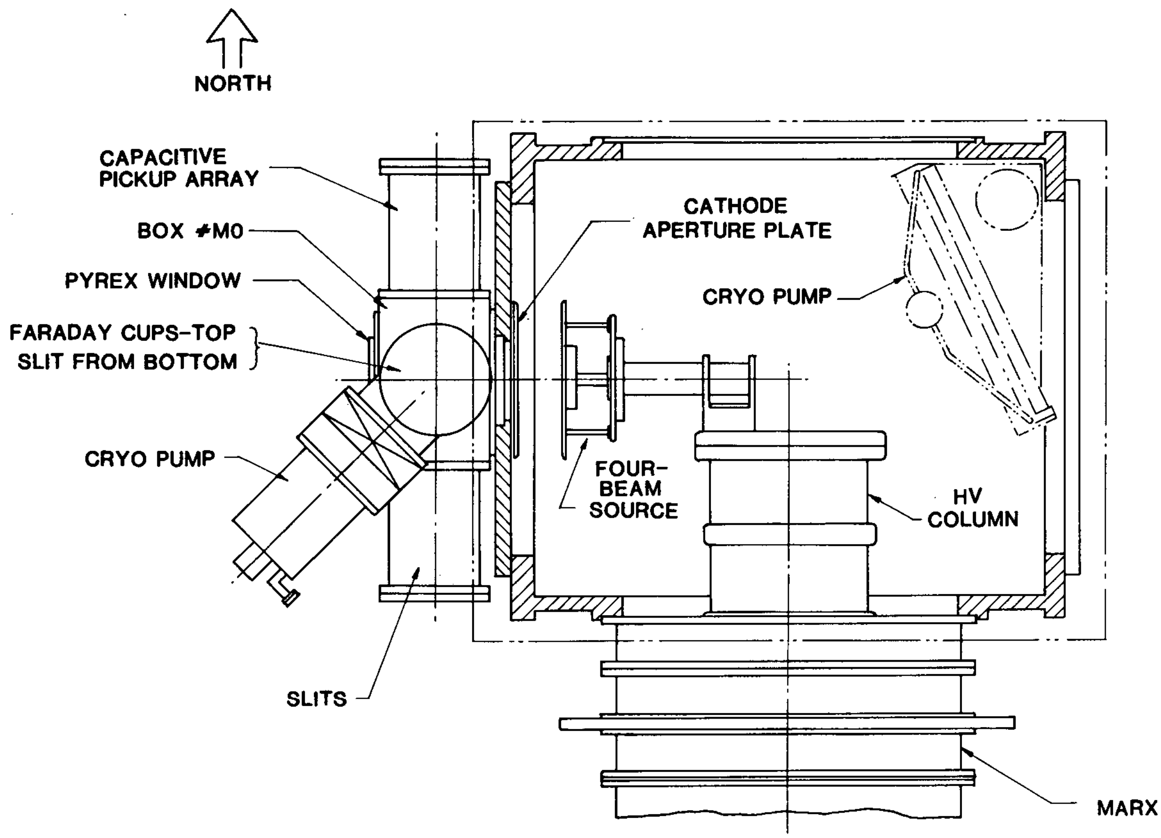

FIG. D6-1

MBE-4 PHASE 1A INJECTOR INSTALLATION AND TEST CONFIGURATION.

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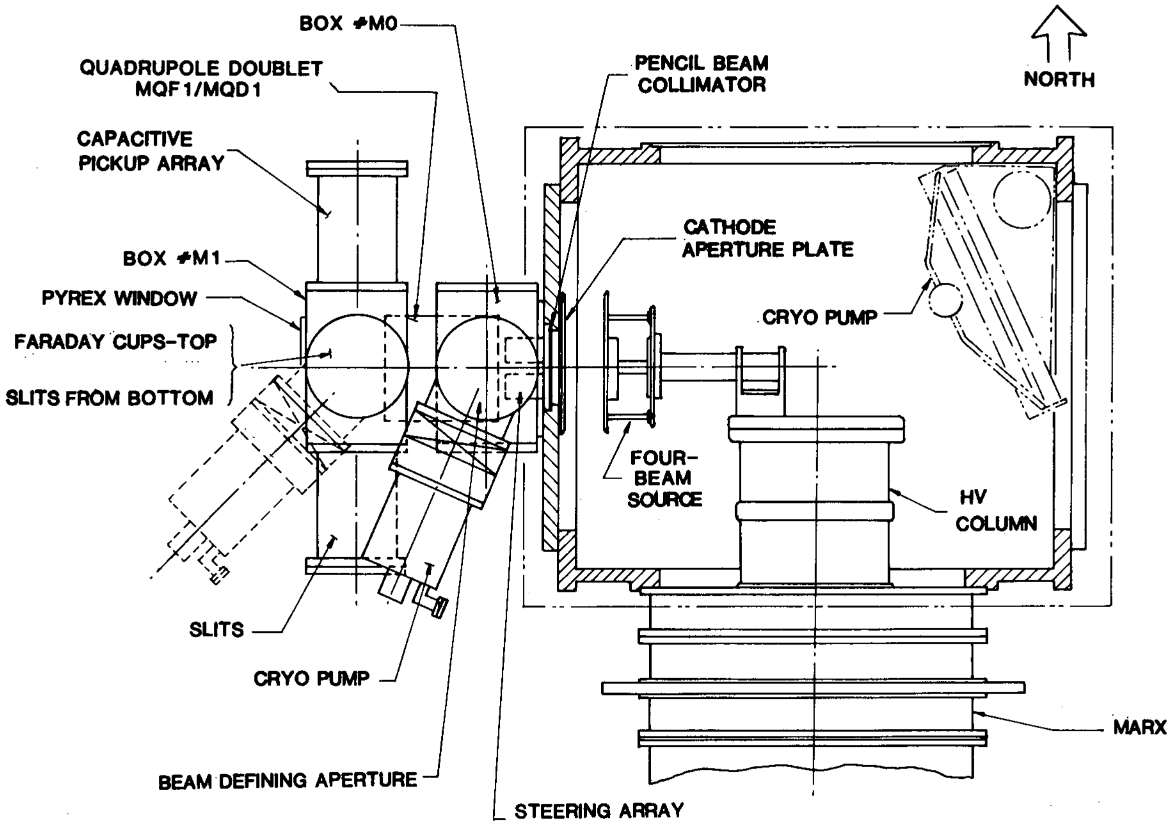

FIG. D6-2

MBE-4 PHASE 1B INSTALLATION/TEST CONFIGURATION (through BOX #M1).

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E. Accelerator Apparatus

The Accelerator Apparatus (Ref: Fig. C3) accepts the four ion beams from the Beam Conditioning Unit and then, by pulsed induction, accelerates the beams to higher energy with voltage waveforms that also shorten the time duration of the beam pulses as well. Electrostatic quadrupoles provide focussing for the ion beams. In its planned configuration, the MBE-4 Accelerator Apparatus will consist of six Accelerator Sections, each containing five quadrupole doublets interspersed with four accelerating gaps. Each accelerating gap has a vacuum-tight insulator assembly around which are placed the induction cores used for acceleration. A beam-sensing box is located at the exit of each Accelerator Section. The six Accelerator Sections are labeled "A" through "F". The six Sections contain a total of 24 accelerating gaps which are capable of accelerating the beams to energies approaching 1.0 MeV. Further Accelerator Sections could be added, if desired.

E1 Induction Acceleration

The beam is accelerated by voltage induction at the four accelerating gaps that are interspersed between the five quadrupole doublets in each of the six Accelerating Sections. This gives a total of 24 accelerating gaps. The induction acceleration configuration at one gap is shown schematically in Figure E1-1. The induction cores can be viewed as pulse transformers with the induction pulsers supplying pulsed power to the primary windings. A strap around the induction core group (all of the cores at one gap) forms a secondary circuit which applies a voltage to the accelerating gap that is equal to the sum of the primary voltages of the core group.

E1.1 Induction Insulator

Insulators of the configuration shown in Figure E1.1-1 are built into the vacuum enclosure wall to permit the induction voltage to reach the accelerating gaps. They consist of Re-X* glass-ceramic tubular insulators into which stainless steel tubulations are imbedded at both ends during manufacture (*Re-X is a trademark of General Electric Co). Metal flanges incorporating metal chevron vacuum seals are added to both ends of each insulator assembly so that they can be

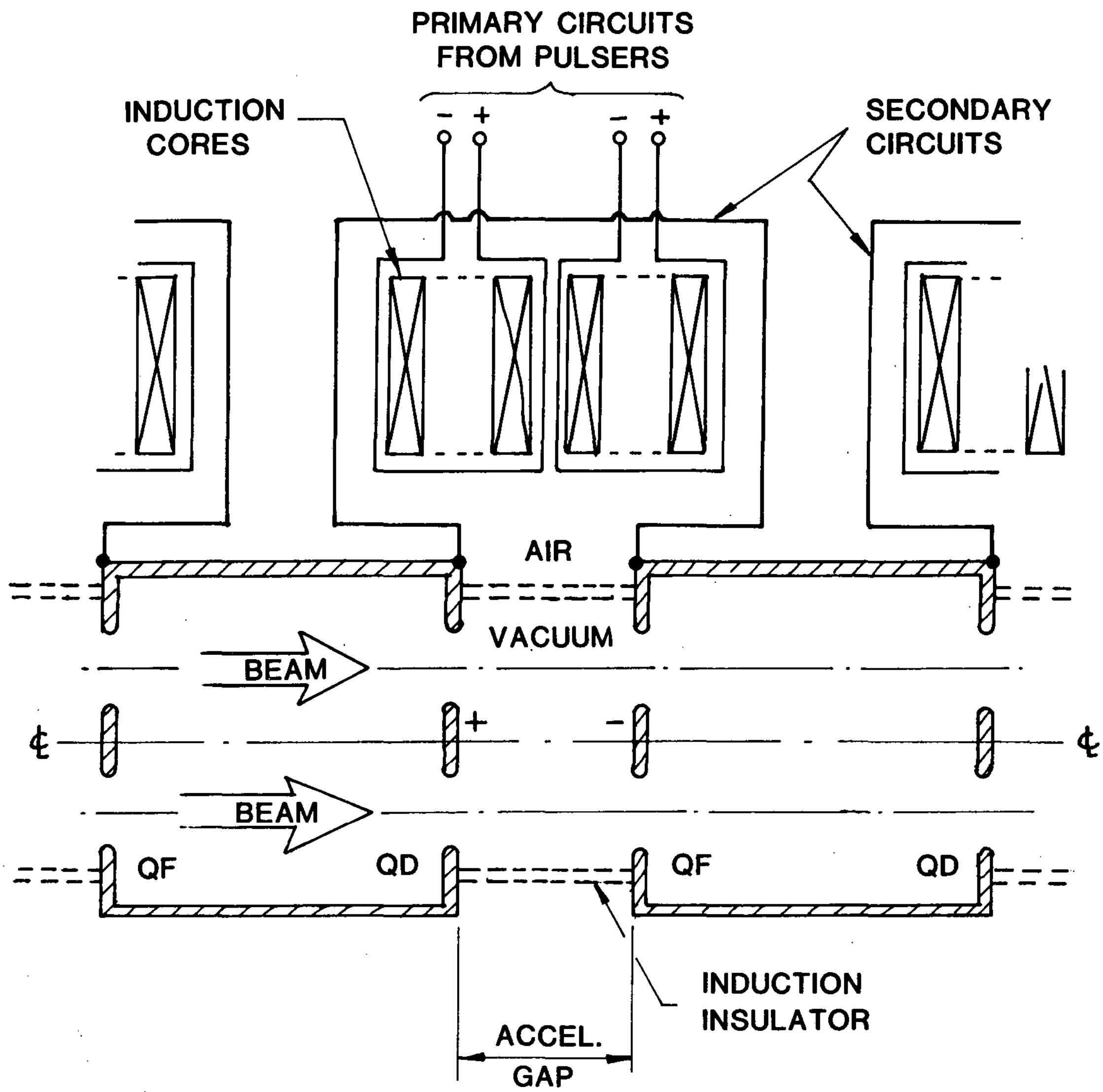

FIG. E1-1

MBE-4 INDUCTION ACCELERATION DIAGRAM

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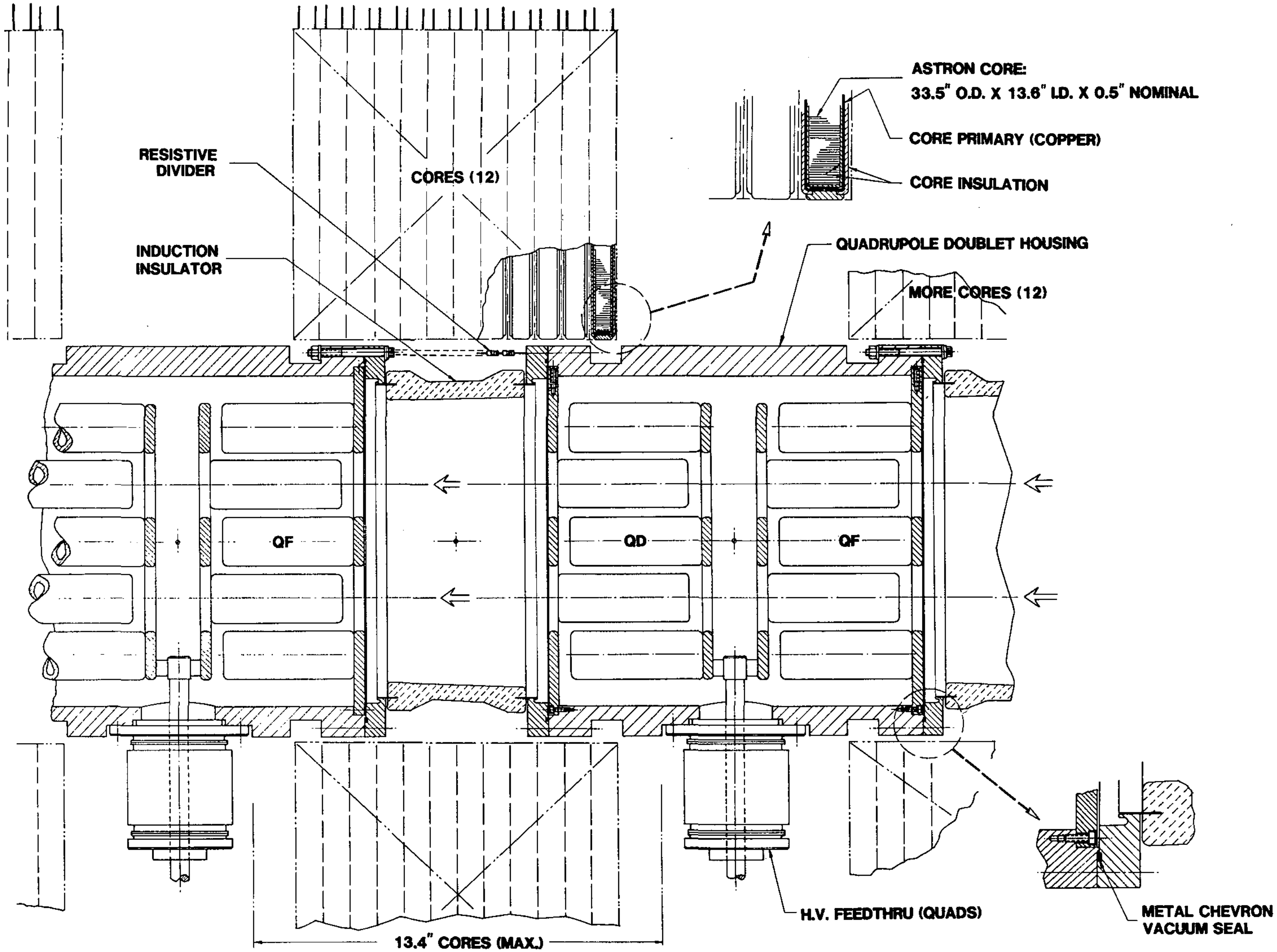

FIG. E1.1-1
INDUCTION INSULATOR AND CORE CONFIGURATION

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joined to the adjacent quadrupole doublet housings. The metal chevron seals have been fully qualified by numerous tests.

E1.2 Induction Cores

The budgetary restraints mentioned earlier suggest that existing induction cores and core material should be used to the maximum extent practical. Table E1.2-1 lists the cores and core material that are now on hand and can be considered for use in MBE-4. The approximate flux swing, in millivolt-seconds, available from these cores is also listed. Current plans contemplate using 48 Astron nickel-iron cores in Accelerator Section "A" but with a small amount of material removed from the inside diameter to permit them being installed around the induction insulator assemblies with adequate clearance for insulation, primary windings, and a voltage-measuring resistive divider. Separate primary connections will be available for each core permitting various hookups to the pulsers. This core arrangement is also shown in Figure E1.1-1. It is planned that most of the remainder of the core material listed in Table E1.2-1 will be used for cores in Accelerator Sections "B" through "F" with many of these having to be rewound into new cores from the existing material.

TABLE E1.2-1

INDUCTION CORES AND CORE MATERIAL
AVAILABLE FOR USE IN MBE-4

MATERIAL	DIMENSIONS (ODxIDxW)	QUANTITY	APPROXIMATE MILLIVOLT-SECONDS EACH	TOTAL
Metglas* 2605SC .001"	36"x24"x2"	2	11.6	23.
Metglas* 2605CO .001"	36"x24"x2"	2	16.6	33.
Metglas* 2605S-2 .001"	36"x24"x2"	2	12.8	26.
Metglas* 2605S-3A .001"	36"x24"x2"	2	7.7	15.
Metglas* 2605CO .001"	2"w Tape	700 kg	-	100.
Astron Ni Iron .001"	33.5"x13"x0.5"	92	6.8	626.
Astron Ni Iron .001"	24"x9.25"x0.5"	20	4.9	98.
3.25% Si Steel .002"	33"x13"x1.37"	26	23.9	621.
3.25% Si Steel .002"	Rectangular: 33.5"x18.5"inside x 4" build	6	13.7	82.
3.25% Steel .002"	14"w Tape	8000 lbs	-	764.
			TOTAL	2388.

*Metglas is Allied Corporation's registered trademark for amorphous alloys of metals.

E1.3 Induction Power System

The accelerating voltage waveforms for MBE-4 are under active study by the HIFAR staff and will continue to be studied, developed and improved throughout the duration of the MBE-4 program. Some examples of accelerating waveforms being considered for incorporation into MBE-4 are shown in Figure E1.3-1. Analysis has suggested that ideal waveforms would be a slightly-upcurved ramp at the first few gaps, a rising trapezoid at the succeeding few gaps and a squarish pulse for the remaining gaps. In particular, the analysis indicated that discontinuities in slope (e.g., firing of a pulser during beam transit) produce klystron-like ion current spikes, which should be avoided. The ideal shapes are not readily achieved in real circuits. It appears that combinations of conventional "flat top" pulses plus upward curved "1 - cos at" pulses might produce adequate approximations to the desired shapes. For Accelerator Section "A", it is planned that several of both types of pulsers will be built for the initial MBE-4 experiments. Subsequent induction pulsers may be of the same or of different configuration depending on the results of further analysis and experimentation.

E2 Timing System

A comprehensive timing system is required to properly time and coordinate the many devices including the Marx HV Generator, diagnostic/beam sensing devices and the induction pulsers. The system needs to be flexible so that timings can be changed readily and so that additional devices can be accommodated.

The planned timing system is shown schematically in Figure E2-1. The master unit is synchronized to line frequency so that MBE-4 will be triggered at the same, but variable, phase relative to the AC mains. The master unit can be triggered externally, for example by computerized diagnostic equipment, or internally at a fixed repetition rate period variable from one to five seconds. The master unit provides clock and gate pulses to the time delay units.

MBE-4 ACCELERATING WAVEFORMS

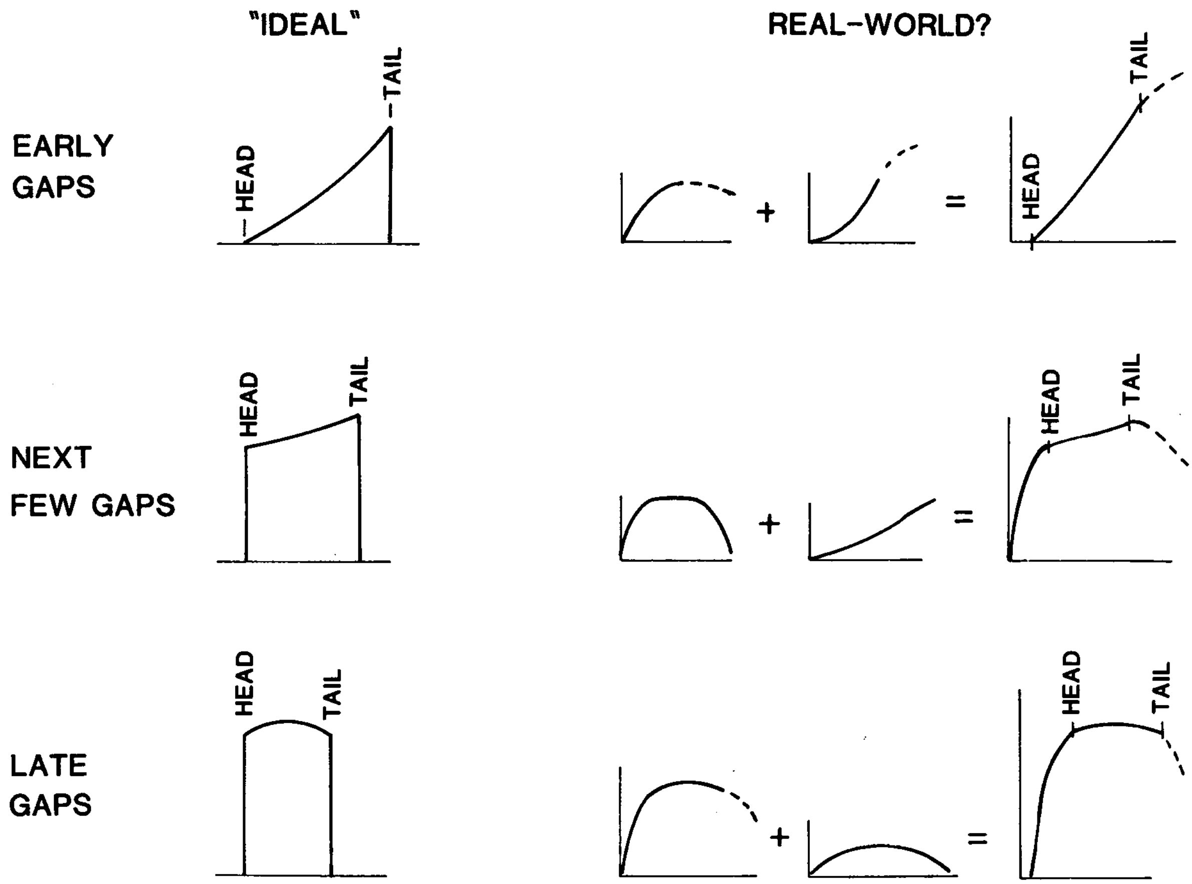

FIG. E1.3-1

EXAMPLES OF THEORETICAL AND REAL WORLD WAVEFORMS BEING CONSIDERED FOR INCORPORATION INTO MBE-4.

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MBE-4 TIMING

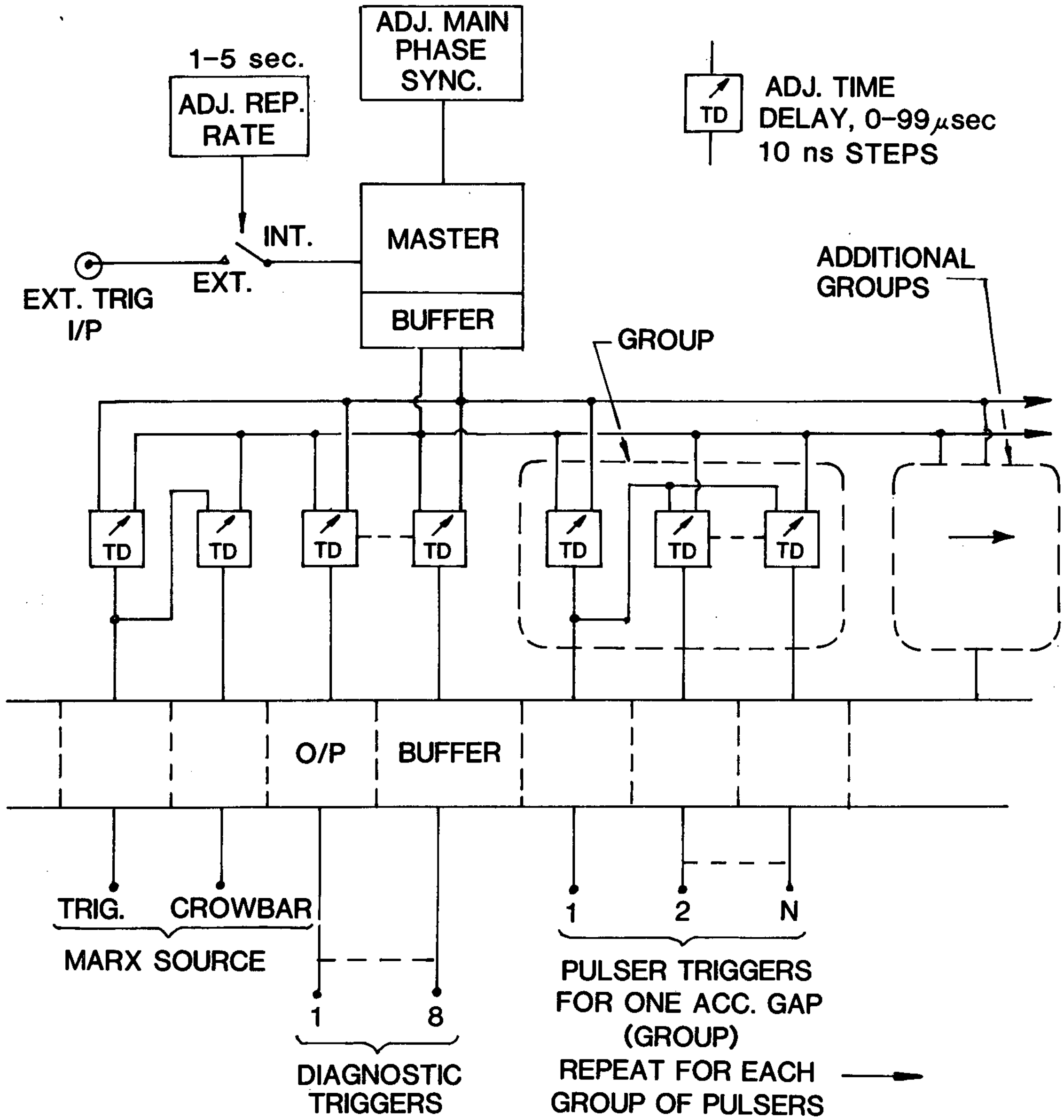

FIG. E2-1

ELECTRICAL CIRCUIT SCHEMATIC FOR THE TIMING SYSTEM

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The time delay units are modularized with eight time delay units in one CAMAC module. Current plans call for 64 units; eight units for each of the six Accelerator Sections plus 16 units for diagnostics and the Marx HV Generator. The system can readily accommodate additional units, if needed. The time delay of each unit can be adjusted from 0-99 microsecond delay with 10 ns resolution. The input to a time delay unit can come from the master unit or from the output of another timing unit, thus providing flexibility. Output buffering is provided because of the noisy electrical environment. Setting of time delays will be done manually initially, but this can be computer-controlled at a later time.

E3 Accelerator Quadrupoles

The configuration and dimensions of the accelerator quadrupole arrays are tentatively planned to be identical to the matching quadrupole arrays described in Section D3.3. Ongoing analysis may indicate a change in dimensions, perhaps of electrode and aperture diameters. Each accelerator quadrupole doublet will have only one high-voltage feedthrough at the vacuum wall because both the F and D arrays of a doublet operate at the same voltage. As the ion beams gain energy down the length of MBE-4, an ever greater quadrupole voltage is required. To provide these voltages, five HV power supplies are included for Accelerator Section A and four HV power supplies for each of Accelerator Sections B through F, for a total of 25 HV power supplies. Only four supplies are provided for the later sections because the first quadrupole of these sections can operate at the same voltage as the last quadrupole of the previous section since the beam-sensing box between them provides no acceleration. The electrical circuit for these power supplies is the same as shown in Figure D3.3-4 for the matching quadrupoles, except that those for the later Accelerator Sections will have voltage ratings higher than the 30 kV shown.

E4 Diagnostics (Accelerator Apparatus)

Beam-sensing devices are provided to determine that the ion beams are being transmitted properly along the length of MBE-4 and to assess the beam characteristics at the exit of MBE-4. These devices are listed in Table E4-1, shown in Figure D3-1, and are discussed in more detail hereafter. The diagnostic devices can be relocated to other beam-sensing boxes, if desired.

TABLE E4-1

DIAGNOSTIC DEVICES IN MBE-4 ACCELERATOR APPARATUS

DEVICE	POSITION	PURPOSE
Faraday Cup Array (6 total)	Box #5, 10, 15, 20, 25, & 30	Measure beam current independently in all four ion beams.
Emittance Sensors, vertical	Box #30	Horizontal slits to measure vertical emittance of all four ion beams.
Emittance Sensors, horizontal	Box #30	Vertical slits to measure horizontal emittance of all four ion beams.
Harps, vertical (5 total)	Boxes #5, 10, 15, 20, & 25	Horizontal wire arrays to measure vertical position and height of all four ion beams.
Harps, horizontal (5 total)	Boxes #5, 10, 15, 20, & 25	Vertical wire arrays to measure horizontal position and width of all four ion beams.
Energy Analyzer	After Box #30	Ninety degree electrostatic spectrometer to measure energy of one of the four ion beams.
Steering Arrays	Boxes #20 & 25	Test steering of ion beams with momentum gradient along beam bunch length

E4.1 Beam Sensing Boxes (Accelerator Apparatus)

These boxes are tentatively planned to be similar to those described in Section D3.4 for the Beam Conditioning Unit. They can accommodate the same types of devices.

E4.2 Faraday Cup Array (Accelerator Apparatus)

It is planned that the Faraday Cup Array and its associated electrical ciruitry will be similar to the four-cup arrangement described earlier in Section D3.5. As mentioned there, the Faraday Cup Array may be superseded by the Capacitive Pickup Array if the latter proves fully successful in use.

E4.3 Emittance Sensors (Accelerator Apparatus)

It is contemplated that the Emittance Sensor Arrays and their associated electrical circuitry will be similar to the Emittance Sensor Arrays described earlier in Section D3.7.

E4.4 Harps (Accelerator Apparatus)

The Harps and their associated electrical circuitry are contemplated to be similar to those described in Section D3.8. One 120-channel track-and-hold unit will be switched manually among the five vertical and five horizontal arrays.

E4.5 Energy Analyzer

An electrostatic energy analyzer with fast time resolution is being constructed. It incorporates 90-degree deflection with a plate separation of 1.00 inch and a bending radius of 18.0 inches. Provisions will be made at the exit of MBE-4 so that this spectrometer can be accommodated. As currently planned, it can analyze Cesium ion beams up to approximately 400 keV energy. With power supplies of higher rating it may be capable of handling energies approaching 1.0 MeV.

E4.6 Steering Arrays (Accelerator Apparatus)

It is planned that electrostatic steering arrays similar to those described in Section D3.2 and shown in Figure D3.2-1 will each be mounted on a probe drive and then installed at the selected beam sensing box. The probe drive will permit the steering array to be withdrawn from the ion beams so that other diagnostic devices can be used at the same location. These steering arrays can be used for dynamic steering tests as discussed in Section G1.7. Each steering array will require independent variable pulsers for both x and y transverse directions of each of the four ion beams.

E5 Support and Alignment (Accelerator Apparatus)

The five quadrupole doublets and the four induction insulator assemblies of each Accelerator Section are bolted together into a rigid pre-aligned unit. Metal chevron seals are used to provide accurate alignment of these components as well as forming a vacuum seal. Tests have demonstrated the effectiveness of these seals for this purpose. Each end of each Accelerator Section is supported by a structural stand fixed to the heavy concrete floor. Longitudinal compliance is provided by a bellows at one end of each Accelerator Section. Alignment within a tolerance of approximately 0.1 mm (0.004") will be achieved relative to monuments in the concrete floor either by bore-sighting or by taking vertical and horizontal offsets from the accurately machined outside diameters of the quadrupole doublet housings. The induction core groups are supported by separate stands to the floor because the cores need not be accurately aligned.

E6 Vacuum System (Accelerator Apparatus)

The walls of the quadrupole doublet housings, the induction insulator assemblies and the beam sensing boxes make up the vacuum enclosure for the Accelerator Sections. The Accelerator Sections are pumped by cryopumps located at each beam sensing box. This should result in a pressure of less than 3×10^{-7} Torr. Valves are included for regeneration of the cryopumps and for roughing of the vacuum system. Ionization and thermocouple gauges to measure pressure are located at each beam sensing box. The arrangement for Accelerator Section "A" is shown schematically in Figure D4-1. A similar arrangement occurs for the succeeding Accelerator Sections. Control and power for the vacuum system will be coordinated with those for the Injector System.

E7 Control and Monitoring (Accelerator Apparatus)

MBE-4 will initially operate in a manual mode with a hardwired interlock system to preclude high voltage hazards. On/off switches, time delays, voltage level controls and system status will be provided and grouped at the central electronic racks. Computer control has been provided for and will be implemented as time permits, but the interlocks will remain hardwired.

Monitoring of analog voltages will be accomplished by a data logger located near the level controls. The time delay monitoring is by digital displays located in the module front panels. Computer monitoring of the foregoing has been provided for and will be implemented as time permits. Induction voltages, as well as the voltage generated across acceleration gaps, will be monitored using a voltage divider and an oscilloscope.

E8 Installation (Accelerator Apparatus)

Phases 1A, 1B and 1C for installation of the Injector System (including Beam Conditioning Unit) were described in Section D6. It is contemplated that the Accelerator Sections will be installed in phases also. Phase 2A will include installation of Accelerator Sections "A", "B" and "C", but with induction acceleration limited to the first four gaps. After acceleration in Accelerator Section "A", the ion beams will "drift" to the end of Accelerator Section "C". This arrangement will permit early observation of the four ion beams, including longitudinal bunching effects. Phase 2A will conclude the FY85 installation work.

The remainder of the Accelerator Sections will be fabricated and installed as part of Phase 2B as well as a significant addition of induction cores and pulsers. Phase 2C includes fabrication and installation of the remainder of the induction cores and pulsers.

F SCHEDULE.

The schedule objectives for fabrication and installation of MBE-4 are shown in Figure F-1. The work is subdivided into phases as described in Sections D6 and E8. This schedule is brisk and optimistic, but achievable. Since some of the components are developmental, there is a chance that unforeseen events may cause a slippage in the schedule.

MBE-4 SCHEDULE OBJECTIVES

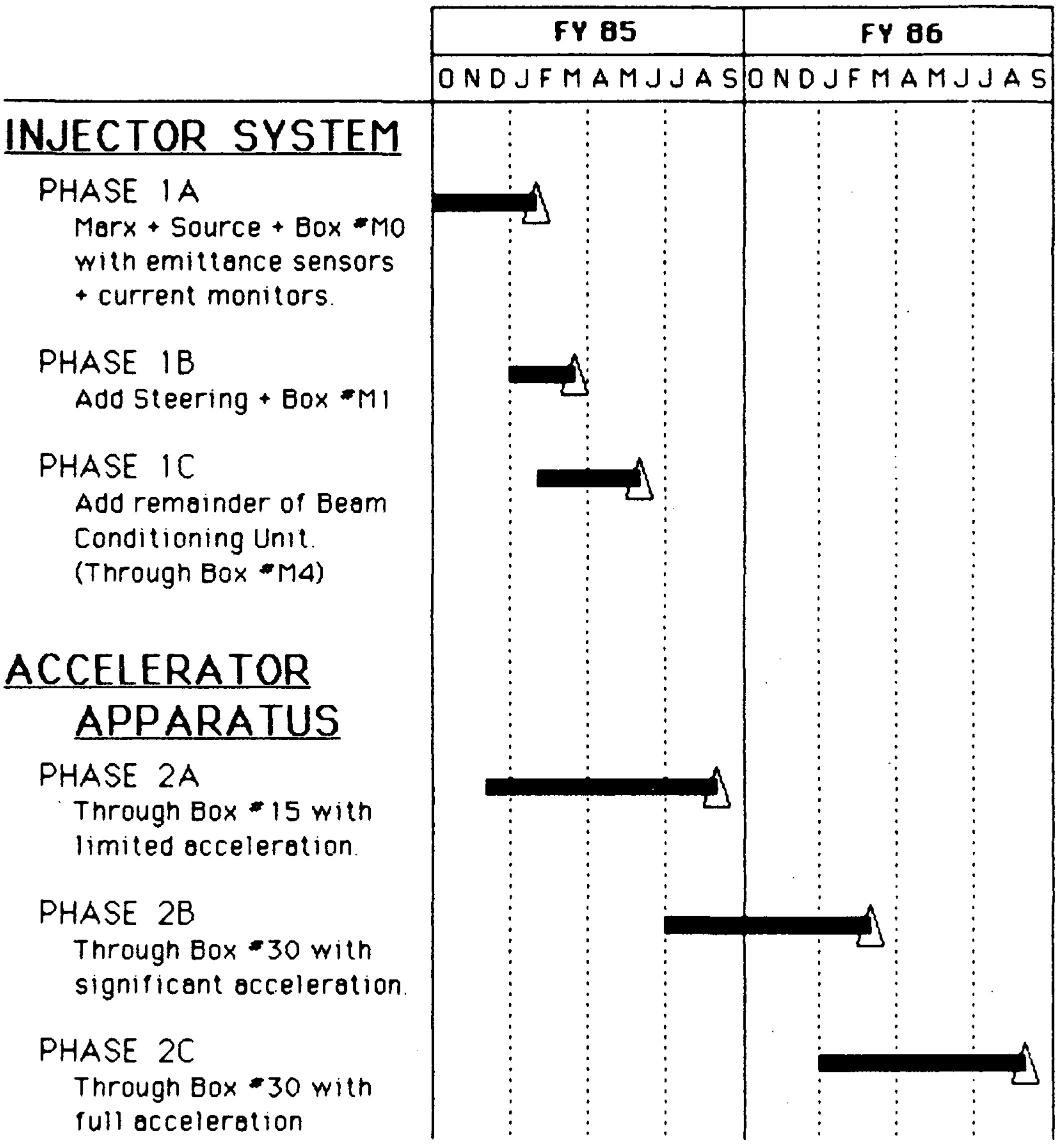

Figure F-1

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G. MBE-4 Experimental Program

The objective of MBE-4 is to conduct tests on a pilot scale addressing the feasibility and credibility that the multiple beams in the future HTE will be able to achieve the current, energy, phase space density, current amplification, etc., needed for significant pellet heating.

A comparison of the parameters of the MBE-4 and the HTE accelerators is presented in Table G-1. Note that the actual length of MBE-4 is about 3% of that of HTE, but the lengths of the two facilities measured in units of the injected pulse length are comparable. This implies that similar longitudinal beam dynamics issues will be encountered in the two experiments. The granularities due to (a) spaced acceleration kicks, and (b) quantized voltage steps are more severe than for HTE. Thus, we can study effects resulting from strong voltage kicks and the effectiveness of plasma waves in smoothing out these granularities.

A longitudinal computer code has been developed by means of which acceleration schedules can be designed. Voltage waveforms and timing are adjustably varied in a calculation which predicts current waveforms (I(t)) and kinetic energy waveforms (E(t)) at specified locations (z) down the machine. This is in exact analogy to the experimental procedure, by which a given set of voltage waveforms will be employed and the diagnostics will yield measured values of I(t) and E(t).

The transverse behaviour of the beam will be studied by means of profile and emittance measurement. The extent of the transverse oscillations induced during acceleration will be crucial to the determination of optimum acceleration schedules.

Table G-1

COMPARISON OF THE MBE-4 AND THE HTE ACCELERATORS

Parameter	MBE-4	HTE
Number of beams	4	16
Injection energy	0.2 MV	2.0 MV
Final Energy	0.5-1 MeV	125 MeV
Energy Amplification	2.5-5	62
Injection pulse duration	2.5 μsec	6.0 μsec
Final pulse duration	0.5 μsec	0.3 μsec
Injection current/beam	5-10 mA	300 mA
Final current/beam	20-40 mA	6 Amp
Current amplification	4	20
Ion	Cs	Na
Lattice period	0.46 m	0.6 m (and up)
Peak gap voltage	33 kV	250 kV
Accelerating gaps	24	500 (approx.)
Cores/gap	2-8	15-20
Length	16 m	450 m
Length/Injected pulse length	12	18
Perveance: Injection	4.2×10^{-4}	3.3×10^{-4}
Final	1.2×10^{-4}	1.3×10^{-5}

G1 Accelerator Physics Addressed by MBE-4

The MBE-4 experiment will address many of the ion induction linac issues expected to be encountered in the HTE. A partial listing of these follows.

G1.1 Effects Produced by Multiple Beams

In the region between focussing elements, the self field of one beam can influence its neighbors. Theory indicates that effects due to this beam-beam coupling are negligible, which the experiment is expected to confirm.

G1.2 Bunch Length Control

MBE-4 will be able to achieve a current amplification factor through the experiment of as much as 4 or more. This will require that the length of the bunch be carefully controlled, implying that longitudinal beam spreading due to space charge must be properly compensated.

G1.3 Induction Acceleration and Current Amplification of Ion Beams

HIF linacs must not only accelerate beams, but must axially compress them as well. This requires carefully shaped accelerating waveforms to keep the bunch length short yet avoid overbunching the beam causing a loss of particles. In scaled parameters, MBE-4 will be able to accelerate beams much more aggressively than necessary for HTE. Obtaining initial practical compromises between the ideal accelerating waveforms and those that can be reasonably synthesized in the laboratory will be one of the most important experimental results.

G1.4 Longitudinal Ion Beam Dynamics

It is believed that the longitudinal dynamics of ion beams is understood, both with and without space charge effects. However, it is important to confirm this experimentally, which can be done on MBE-4.

G1.5 Longitudinal/Transverse Coupling

Will longitudinal bunching and waves produce transverse effects or vice versa? None is anticipated, but there may be surprises so it is important to demonstrate the absence of these effects experimentally.

G1.6 6-Dimensional Emittance Growth

Experiments on SBTE thus far have been directed at determining the transverse emittance growth of drifting space-charge-dominated ion beams. MBE-4 will begin to study the transverse and longitudinal emittance growth of beams with a head-to-tail axial velocity shear. Errors in acceleration can produce axial heating and longitudinal emittance growth. These will be damped to some extent by plasma or space charge waves. The experiment will provide the initial answers on the effectiveness of these waves in damping errors produced by imperfect acceleration.

G1.7 Beam Position Control and Steering

Unavoidable fabrication and alignment errors may cause problems in longer ion accelerators such as HTE. Satisfactory techniques for guiding or steering the beams through the accelerator must be developed. The steering is complicated by the fact that, after the start of acceleration, the beam head and tail will have different energies. Thus, an imposed steering impulse must account for this change in beam rigidity. The situation is still further complicated by the fact that different energies from head to tail of the beam produce different transverse oscillation wavelengths. Some ways down the length of the accelerator, this can result in different transverse positions and angles for the head, middle and tail of the beam. Consequently, the desired steering impulse may need to vary significantly during the transit of the beam pulse through a steering array. MBE-4 will provide a scaled experiment for assessing some of the difficulties in steering beams with axial velocity shear.

G1.8 Reduced Voltage Injection

By reducing the Marx HV Generator voltage, ion beams of reduced energy and current can be produced. With the planned induction acceleration capability, this would permit achievement of still greater energy and current amplification ratios.

G2 Issues Not Fully Addressed by MBE-4

There are several issues that will not be well modeled by the MBE-4 experiments.

G2.1 Number of Pulsers

A long accelerator such as the HTE will contain thousands of individual pulsers that contribute to the accelerating waveforms and thus to the final beam energy. The cumulative effects of the pulser switching transients on the beam current and energy are expected to be damped by both beam space charge and the statistics of large numbers. MBE-4 is expected to have 50-100 pulsers and can provide important modeling results, but clearly cannot be totally definitive.

G2.2 Transition to Magnetic Focussing

At low energies electrostatic quadrupole focussing allows the largest beamlet currents to be accelerated. However, for HTE, as soon as the particle speeds exceed approximately .05 c, a transition to magnetic quadrupole focussing will be made. The favorable scaling with velocity allows shortening of the beam bunch as well as acceleration which allows current amplification to proceed at a rate faster than the beam speed. MBE-4 is not well suited for examining the transition from electrostatic to quadrupole focussing or for studying the physics of ion beam focussing in magnetic quadrupoles. (Note that MBE-16 was designed to reach an energy where the transition to a magnetic lattice was possible and could be tested.)

G2.3 Fabrication and Alignment Errors

Issues associated with alignment errors and tolerance buildup in long accelerating structures are addressed only in a scaled way. Although some information on the effects produced by these errors and ways of overcoming them will be gleaned, the extrapolation to HTE will require careful simulation studies and further engineering and component development.

G2.4 Injection Energy

The tests on MBE-4 will be at one-tenth the injection energy contemplated for HTE. It is strongly believed that the physics issues addressed by MBE-4 are directly scalable to higher energies, however, one can have absolute confidence only after they have been actually done at the higher energies.

G2.5 Full-Scale Components

MBE-16 would have demonstrated pulsers, quadrupoles, insulators, etc., of the size and performance contemplated for HTE. In contrast, MBE-4 utilizes scaled down components. Thus, the issue of technology demonstration is only partially addressed and will need to be more fully addressed at a later time.

G3 MBE-4 Future Modifications

Modifications and additions to MBE-4 could provide still further results relative to HTE. Some of these are described below. Such extensions of MBE-4 are not part of the presently-planned scope of MBE-4. The results of the MBE-4 experimental program described earlier will have a significant bearing on the nature and scope of any modifications to MBE-4 that might be considered.

G3.1 Change in Lattice Period

In HTE, the quadrupole lattice period increases in length stepwise in order to provide optimal focussing as the ion beam energy increases down the length of HTE. At such step points, special voltages need to be applied to the adjacent quadrupoles to provide matching of the ion beams from the earlier lattice period to the longer lattice period. The greater energy of the tail of the beam pulse relative to the head necessitates that the voltages on the adjacent quadrupoles be time-varying if perfect matching is to be achieved. A test of this process can be performed on MBE-4 by inserting spacer rings into the modular spacing of MBE-4 to produce a longer lattice period, say in Accelerator Section "F".

G3.2 Magnetic Quadrupoles

As mentioned in Section G2.2, an ion beam velocity of the order of 0.05 c is needed for magnetic quadrupoles to be effective. The cesium ion beams in MBE-4 do not approach this. However, replacement of the cesium source with a proton source would provide ions of nearly 0.05 c. Adding a few magnetic quadrupoles to the end of MBE-4 would demonstrate the magnetic quadrupole technology (probably using NdFe permanent magnets) as well as testing the transition from electrostatic quadrupole focussing to magnetic quadrupole focussing. These are directly relevant to HTE as such a transition occurs relatively early in HTE.

G3.3 Additional Length

It is possible to extend MBE-4 out into the Building 58 parking area. It might be enclosed in a temporary shelter. Continuing the quadrupole transport arrays for an additional 10 m would provide a drift space in which to study longitudinal bunching after the full acceleration of MBE-4 has been applied. Naturally, if more induction cores and pulsers were added, higher ion beam energies can be reached. Such additions also would improve the statistics relative to fabrication/alignment errors and to pulsers (if they are added).

G3.4 Many Low-Voltage Pulsers

A possible way of producing specific accelerating waveforms would be to sequentially fire a multitude of low voltage pulsers. For example, at a given accelerating gap, thirty 1.0 kV pulsers or sixty 0.5 kV pulsers might replace three 10 kV pulsers. Whether the ripple impulses produced by such sequential firing are benign to the ion beams would need to be determined. Perhaps semiconductor technology might be suitable for such low-voltage pulsers. If such pulsers were installed along the length of MBE-4, it would provide a quantity of pulsers comparable to that contemplated for HTE so that questions relevant to the large numbers of pulsers in HTE can be better addressed.

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