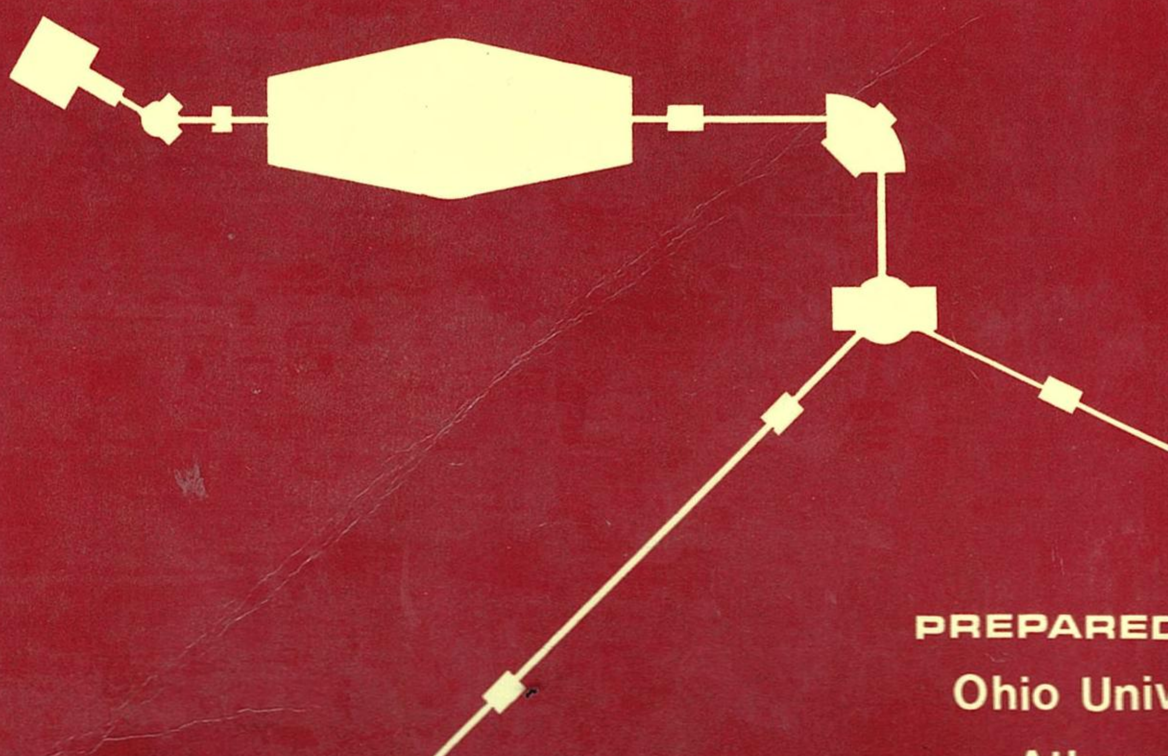
HIGH VOLTAGE ENGINEERING

HIGH ENERGY HIGH INTENSITY TANDEM Van de Graaff ACCELERATOR



PREPARED FOR

Ohio University

Athens, Ohio

HIGH ENERGY — HIGH INTENSITY
TANDEM Van de Graaff ACCELERATOR

prepared for

OHIO UNIVERSITY
Athens, Ohio

CONFIDENTIAL

HIGH VOLTAGE ENGINEERING CORPORATION

December 1967

FOREWORD

The information contained in this proposal has been prepared expressly for the use of the Ohio University Nuclear Physics Faculty and the United States Atomic Energy Commission. It is expressly agreed, by acceptance of this document, that disclosure of technical details, descriptive material, or proposed price information, will not be made outside of the University staff or the United States Atomic Energy Commission.

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INTRODUCTION

This proposal describes in detail a Tandem Van de Graaff high-energy acceleration system, capable of producing previously unattainable ion beam intensities, which is specifically designed to meet the requirements of the Ohio University Nuclear Physics Faculty.

Principal design of this system is based on the incorporation of the most recent advances in negative ion production, and charge-stripping techniques, into sound high voltage engineering concepts utilizing well proven components. Familiarity with the operation of this accelerator will be rapidly attained by the Nuclear Physics Faculty due to their considerable previous experience with Van de Graaff generators.

Comprehensive descriptions are included which discuss each of the sub-systems in this extremely flexible accelerator system. At the end of each major descriptive section, a discussion of expected component lifetimes is given. Critical design criteria are included to illustrate the conservative intent and allow objective evaluation of ultimate performance capability by the reviewer.

The complete system consists of a thoroughly integrated high intensity--low emittance negative ion injector, klystron beam pulsing, an 11.0 MeV (protons) Tandem Van de Graaff accelerator, a post acceleration beam analyzing magnet, and a beam switching yard.

1.0.0 Negative Ion Injector:

The negative ion injector is designed to provide intense beams of negative monatomic hydrogen ions (H_1^-) by direct extraction techniques. Beam currents in excess of 200 microamperes of H_1^- ions are available from this injector with beam emittance characteristics that match the acceptance of the Tandem accelerator.

The low-energy extension has been designed to provide high resolution, maximum transmission and optimum spot sizes. A system of lenses transfers the beam from the diode negative ion source to the object aperture of the tandem accelerator with no clipping or beam loss. Injector negative ion beam output is essentially energy independent above 30 keV and the injector is designed to operate at a maximum potential of 80 kilovolts. Bipotential lens strength, and hence beam focus at the stripper entrance; may be varied independently of the Tandem terminal voltage since the entrance lens of the low energy acceleration tube is virtually eliminated by termination of the entrance field with a high transparency grid.

The first Einzel lens is mounted in the source box and is pre-aligned on its own optical bench prior to installation. It has a gridded five (5) inch aperture which is virtually free from spherical aberration for the beam spot sizes that it handles. This lens focuses the negative ion beam through the inflection magnet and forms an object for the second Einzel lens in the low energy extension.

All necessary vacuum pumps, power supplies, and ion-optical devices, required for ion beam injection into the tandem accelerator at all rated terminal potentials are provided. Provision is made, with an inflection magnet, to magnetically analyze the negative ion beam for elimination of diatomic, and other molecular hydrogen ion species, prior to injection into the Tandem accelerator. Adequate space is allowed for the mounting and use of additional sources with the magnetic inflector. A "zero" degree port is available for future neutral injection, if desired.

COMPONENT LIFETIMES:

During normal operation, with negative hydrogen ion beams, the only injector components which are subject to periodic replacement are the tantalum hollow cathode (used in the diode ion source) and the Einzel lens grids. Cathode life is between 75 and 150 hours. Einzel lens grid life is approximately 1000 hours.

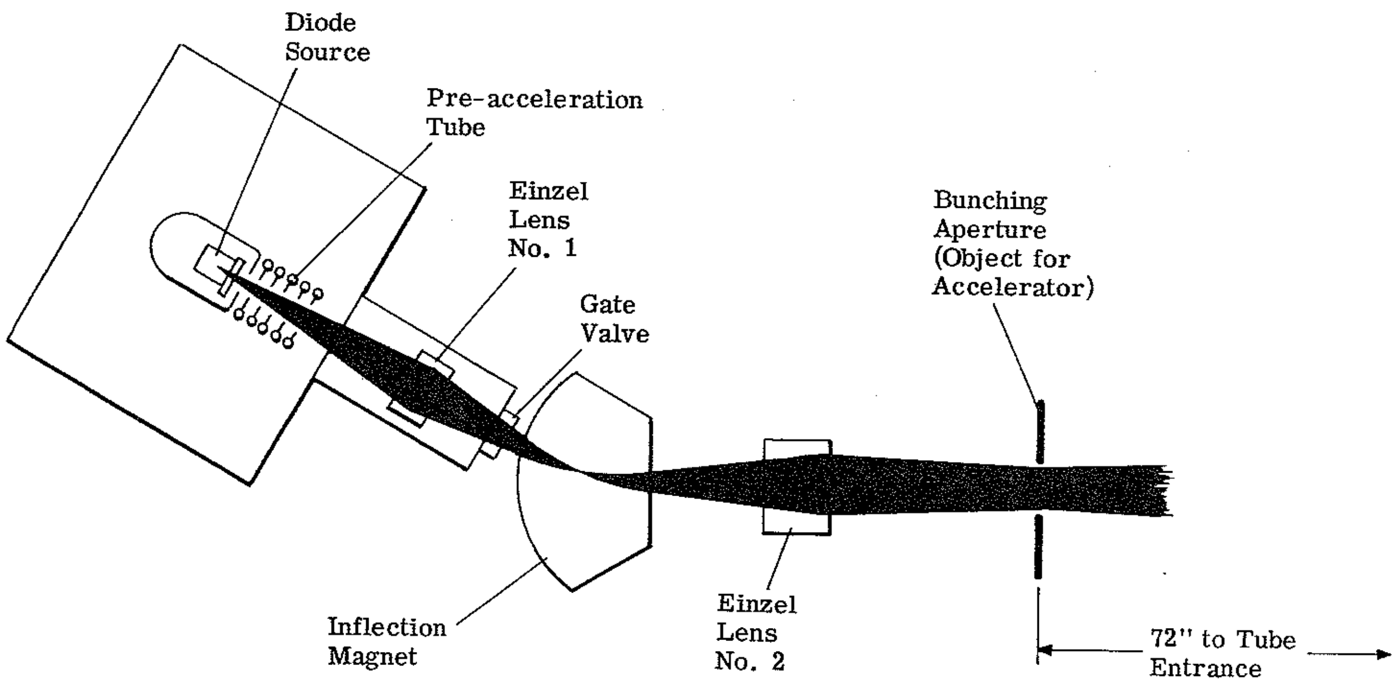


Figure 1 - 80 kV Injector Layout for Ohio University

SECTION 1.0.0

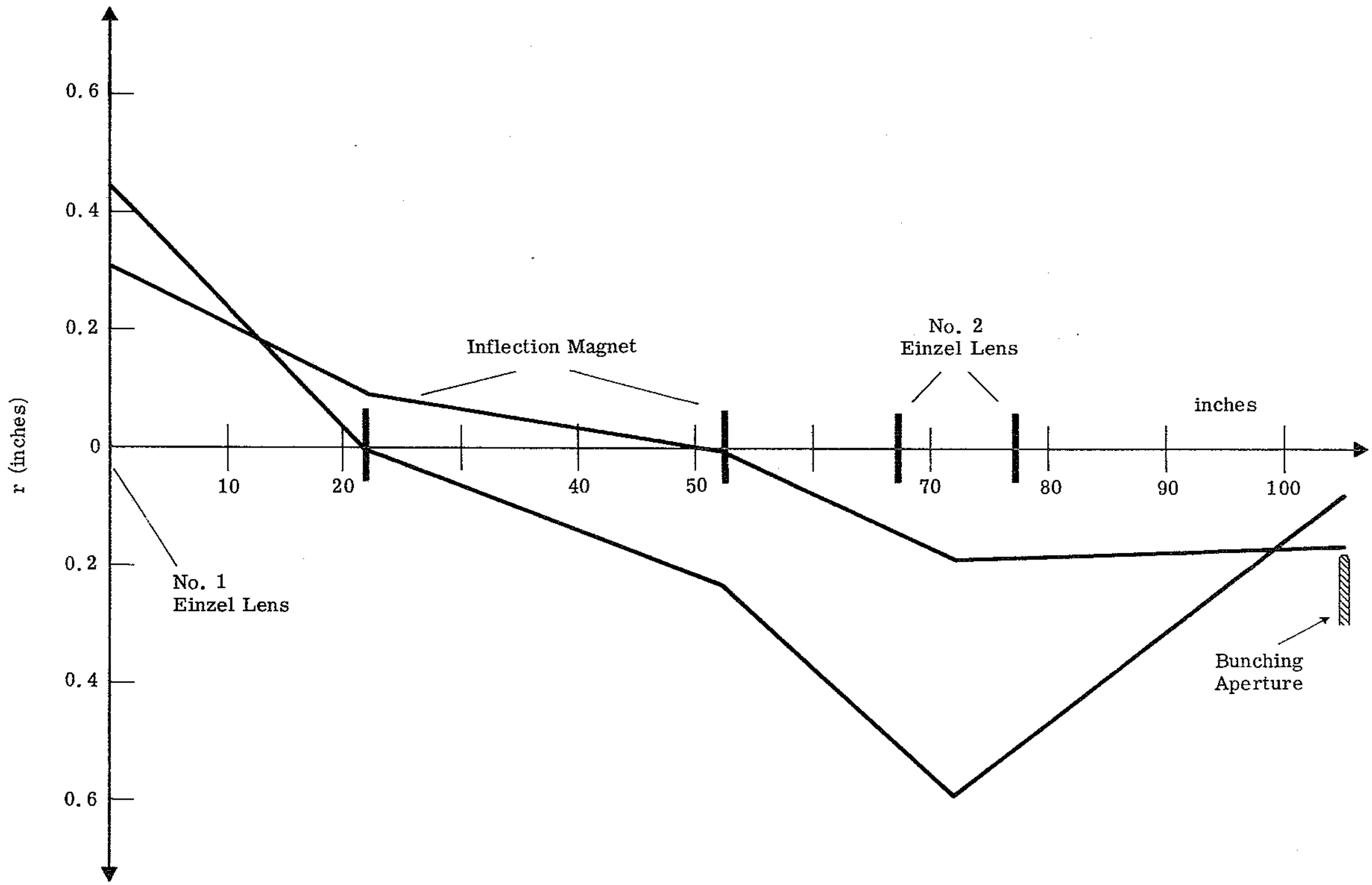


Figure 2 - "X"-ray Trace Trajectories for 80 keV H_1^- through Low Energy Extension

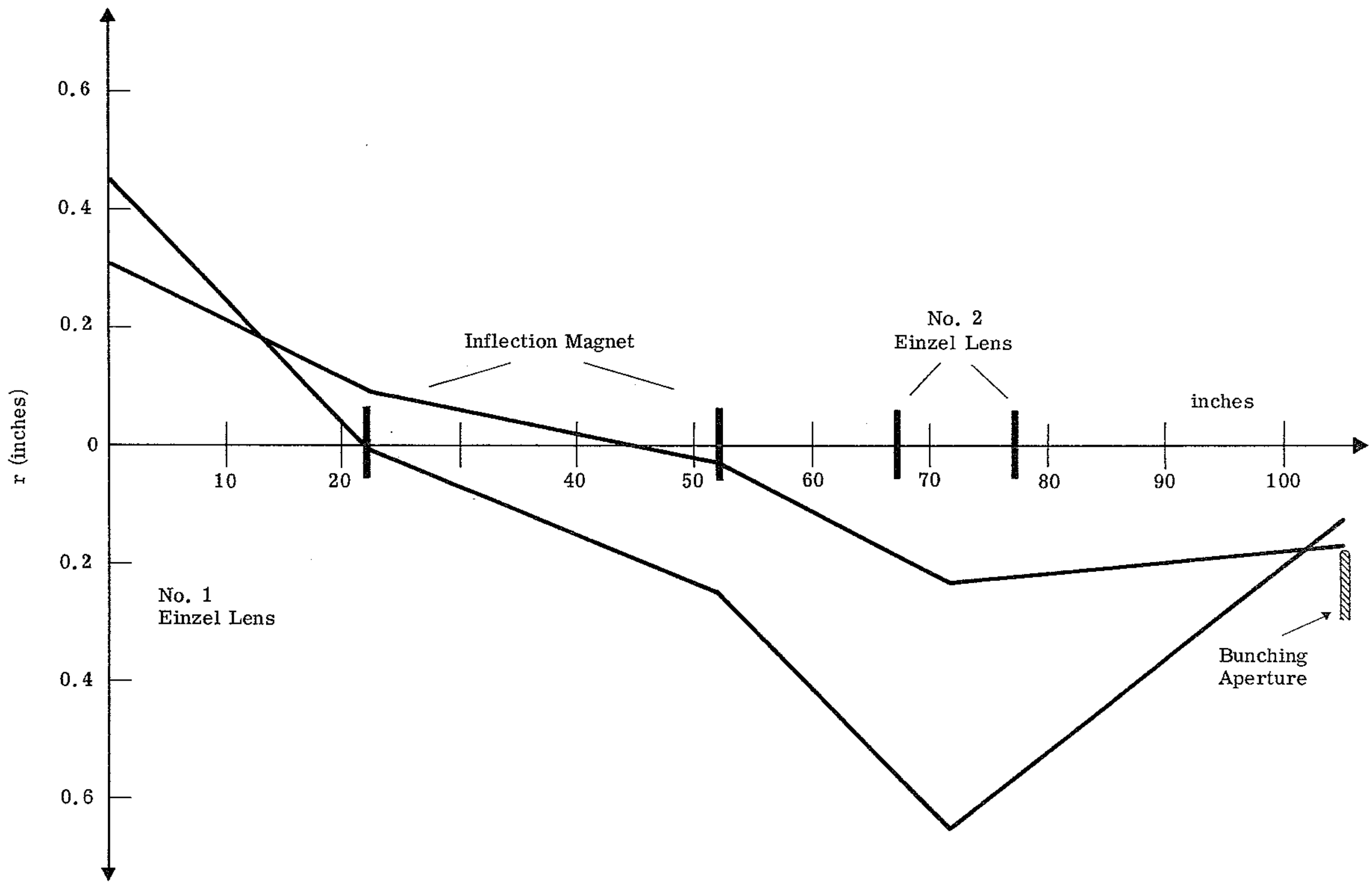


Figure 3 - "Y"-ray Trace 80 keV H_1^-

1.1.0 Diode Ion Source:

The Diode[a] ion source is used, in which negative ions are directly extracted from the source plasma without the intermediate stage of charge attachment from a positive ion beam[1]. This technique uses an intense low energy electron beam for the generation of negative ions by dissociative capture in a gas target followed by direct extraction of the negative ions. A two-stage extraction system with magnetic suppression reduces the loading by electron currents to a negligible value. A carrier gas, usually argon, is introduced through the center of a hollow cathode, together with a trace gas containing the desired element. Negative ions of most elements can be produced with the exception of the noble gases. The most important advantages of this technique are high beam intensities, low emittance, and small energy inhomogeneity.

Gas flow for a .5 milliampere H^- beam is approximately 2.0 atm cc/min. A measured beam emittance of approximately 1×10^{-3} radian-centimeter $MeV^{1/2}$, for a 0.5 milliampere H_1^- beam, is much lower than that of equivalent intensity negative ion beams from collision attachment sources.

Some experimentally observed ion species and currents from the Diode source are tabulated in Table I. It is well proven that this source may readily be used for the production of negative heavy ions with minor if any, modification. This presents a highly desirable flexibility for possible future programs involving the acceleration of heavy ions in the tandem[2].

a -- Figure 1, Appendix

The diode ion source is mounted on a pre-acceleration tube which has an insulating length of nine (9) inches. Maximum operating voltage gradient on this tube is 9 kilovolts per inch. In order to provide adequate pumping for the diode ion source gas flow this tube has been designed to have a conductance of 1600 Torr liters/second.

A closed loop heat exchange system provides demineralized water cooling for the source. It supplies approximately 2.0 gallons-per-minute to the source via non-conducting organic tubing at a temperature of approximately 70°F.

SECTION 1.1.0

TABLE I

"Experimentally Observed Ion Species Obtained from the Diode Source"

ION SPECIES	OBSERVED ION CURRENT (Microamperes)
H_1^-	750
O^-	20
Cl^-	50
Br	50
I^-	30
Bi^-	2.0
$TaFn^-$	1.0
UFn^-	1.0
F^-	100
Al^-	3.0
S^-	10.0
Ta^-	2.0
Ca^-	1.0
K^-	1.0
Ca^-	1.0
B^-	1.0
C^-	1.0

1.2.0 Injector Power Supplies:

The required power supplies for the operation of the Diode source are mounted in a cabinet which is air-insulated for 80 kilovolts. Primary Diode source operating power supplies in this cabinet include:

- Arc Supply
- R. F. Starter
- Source Magnetic Field P. S.
- Lens #1 P. S.
- Lens #2 P. S.
- Vacuum Measurement Chassis
- Two Gas Supplies with Leaks

The main injector power supply is an 80 kV 5 ma D. C. (oil insulated) unit regulated for 0.1 RMS ripple at full voltage and load, 0.5% regulation for ± 10% line variation and 0.5% from 0 to full load. A. C. power is supplied to the insulated high potential cabinet by means of an 80 kV oil insulated 6 kVA 3 phase isolation transformer.

1.3.0 Injector Vacuum Pumping:

Main ion source gas flow is pumped by a ten-inch NRC water-capped oil diffusion pump (4200 Torr-liters/second) which is mounted on the ion source vacuum box, backed with a molecular sieve and a 20 cubic feet/minute Edwards forepump. A ten-inch NRC air-operated gate valve is included for isolation of the pump during poor vacuum situations or source maintenance. Back-streaming of the pumping fluid is reduced to an absolute minimum by the inclusion of a refrigerated baffle mounted in series with the oil diffusion pump. Cooling of this baffle is accomplished by means of a Copeland 3/4 Horsepower freon refrigeration unit. Suitable interlocks are provided to protect the system from contamination in the unlikely event of catastrophic vacuum leakage, power failure, or liquid coolant stoppage.

The source box is used as the mount for the ground potential end of the pre-acceleration tube, and the vacuum system, and also houses the injector Einzel lens. Conductance of the box is far greater than the conductance of any other system components. A low conductance gas baffle at the beam exit of the box isolates the injector vacuum system from the remainder of the low energy extension.

1.4.0 Inflection Magnet:

1.4.1 The double focussing inflection magnet has $\pm 30^{\circ}$ input angles and features low carbon, cast pole pieces combined with a slab yoke structure to ensure maximum magnetic field uniformity consistent with economical construction. Advanced engineering design includes shaped pole pieces to minimize edge saturation; well-cooled monolithic coil structure, generous yoke cross section to ensure more than adequate flux return path, precision alignment marks, and a rigid support base. Maximum (M x E) Z^{-2}, or product number, is 16 at $\pm 30^{\circ}$. Coils are of the water-cooled square copper-wire type, which are wet wound with epoxy resin to insure the most dependable and rugged structural integrity. The magnet has a full 1.25 inch gap and is provided with a three-port vacuum chamber for added flexibility. This chamber is made of water-cooled bronze waveguide and is electrically insulated from the pole pieces so that intercepted ion beam current may be monitored. Yoke structure is such that entrance ports may be placed anywhere in a 180-degree sector. This feature provides unlimited flexibility for additional injector or source legs in the future.

Provision for the insertion of an NMR fluxmeter probe into a homogeneous field volume has been made. During normal operation, the field will be set by peaking the negative ion beam current into the low energy Faraday Cup.

1.4.2 A constant current, ultra-stable, high impedance 4.8 kw power supply is used to power the inflection magnet coils.

Circuit Description:

The power supply circuit consists of three closed loops. The first loop includes the power supply direct current error signal detection amplifier. This high signal-to-noise ratio amplifier can detect error signals of less than 1 microvolt, and is compatible with long leads between the controls and power supply. The second loop amplifier corrects for power line voltage variations and reduces the power supply output current ripple. The third pre-regulator circuit loop maintains a constant voltage across the regulator power transistors. The pre-regulator includes a voltage comparator circuit and a motor-driven variable transformer. This pre-regulator system is used so that sensitive measuring instruments will be free of the effects of high electrical noise levels produced by phase delay silicon (SCR) rectifier circuits.

D-C Signal Wiring:

The effect of contact potentials in the d.c. error detection circuits has been minimized. Gold-plated plugs and receptacles, silver-plated wiring, and cadmium-tin alloy solder at all junctions are used. Interconnections are made with insulated twisted shielded wire, with a minimum numbers of connections. All shields are insulated and grounded at a common point to prevent circulating currents and excessive pickup.

The amplifier circuit is mounted in an electrically insulated and temperature-regulated magnetically and electrostatically shielded plug-in unit. This electrically guarded circuit gives excellent isolation and common mode rejection. Temperature regulation essentially eliminates false error signals from contact or junction potentials produced by variations in ambient or equipment temperatures.

Current Reference Resistor:

The current reference resistor is heat-stabilized Manganin. It is immersed in a temperature-regulated and continuously stirred oil bath oven, which is maintained at its optimum temperature of $50^{o}C$ ($\pm$ 0.3^{o} C) to obtain a stability of less than 5 ppm. The oil bath oven is independent of the temperature or quality of the cooling water. The high dielectric bath minimizes contamination of the voltage signal taps.

Remote Control Panel:

The remote control panel contains a load current meter, the power standby-off, and polarity reversal illuminated push-button switches. The illuminated switches indicate the function and condition of the switched circuit. In addition, the power transistor fuse fault condition is indicated.

The 10-turn, coarse and fine potentiometers, reference voltage zener diode are mounted within a shielded and temperature-regulated enclosure. The zener diode is operated by a constant voltage power supply which uses a special shielded guarded transformer to minimize a.c. capacitive coupling through the circuit.

Specifications:

Model No.	1401-120A
Power Rating (kw);	4.8
Output Current (amps);	0.05-12
Output Voltage (volts);	400
Load Resistance to utilize maximum power rating (ohms):	33
Current Ripple[a]; ma: P. to P.	2.5
A. C. Input, 50/60 Hertz.	
Voltage:	120/208 volts, 3 ∅, 4 wire
kva:	6
Weight: Power Supply (lbs.)	400
Controls (lbs.)	20
Water Requirements:	0.15 gpm per kilowatt, 85 °F., maximum, p = 20 psi.
Dimensions: (inches, h x d x w)	
Power Supply:	59 x 28 x 23
Controls:	3-1/2 x 8 x 19

(a) Maximum ripple having an inductive load time constant greater than 1 second. Field ripple in a solid iron core magnet is reduced by about 0.02 x current ripple.

Specifications, cont'd.

Current regulation:[b]	± 5×10^{-6} for ± 10% line voltage or load resistance change due to I^2R
Current Stability:[b]	± 5×10^{-6} for 15 minutes (short term) ± 1×10^{-5} for 8 hours (long term)
Current Adjust. Resolution:[c]	Coarse -- 1×10^{-3} Standard Fine -- 1×10^{-4}
External Modulation	0 to 1.7 volts, negative, for full current range
Polarity Reversal	Illuminated push-button switch located on the remote control panel sets and indicates polarity. An automatic polarity reversal switch is operated when the variable transformer runs down to zero volts.
Metering:	Assembly Products Stylist Model 361, 0-50 millivolt d.c. with appropriate scale.

(b) Between 20% to 100% of the power supply rating and measured in a magnet field with High Voltage Engineering Corporation's Nuclear Magnetic Resonance (NMR) Fluxmeter.

(c) Continuously adjustable over the entire current range with coarse and fine 10-turn potentiometers. The standard fine control is over any 10% of total current range. Fine controls adjustments over any 1% of total current range are optional.

Specifications, cont'd.

Protection:

1. Power transistor overvoltage zener diode clamp

2. Power diode across power supply output to provide current decay path for inductive loads when the power is turned off

3. The power supply has complete interlock protection with an "interlock-standby on" panel indicator light for:

    a) Phase current unbalance

    b) Cabinet doors

    c) Power transistor fuses

    d) Circuit breakers and fuses for a.c. power

    e) Auxiliary interlocks for magnets or other equipment

    f) Power transistor over current

    g) Power transistor over temperature thermostats

1.5.0 Negative Ion Beam Pulsing by Pre-Acceleration Klystron Bunching:

Pulsed beams of positive ions are obtained, out of the Tandem accelerator, by chopping and klystron bunching the low energy negative ion beam between the injector and the low energy accelerator tube entrance. This system has the definite advantage that all pulsing hardware is conveniently located at ground potential and the angular divergence of the ion beam is unaffected. Details concerning some design considerations involved in the bunching of ion beams by velocity modulation have been described by Anderson and Swann[3].

The injector will contain a beam chopping arrangement whereby the negative ion beam will be swept across an aperture, so that the beam after the aperture will consist of short bursts whose duration in between ten and forty nanoseconds. Retrace circuitry will be provided so that only one beam pulse per cycle of sweeping voltage will be transmitted. The basic sweeping frequency will be (5.0) Megahertz. A count down circuit will be provided so that effective repetition rates of 1/2, 1/4, 1/8, 1/16, and 1/32 of the basic sweeping rate can be obtained.

A klystron-type pre-acceleration buncher capable of producing intense bursts of protons and deuterons will be provided. Conversion from proton to deuteron pulsing will be provided with a conversion time of no more than one hour. The klystron bunching system will be adaptable to beams of He^3 and He^4 ions.

The ion bursts are transmitted[4] through the tandem accelerator in the usual manner, with charge stripping in the high voltage terminal, resulting in short intense ion beam pulses at the target. Best pulsing performance is at Target Number Two.

TABLE I

Comparison of Oscilloscope and Time of Flight Measurements of Typical Pulses of Protons and Deuterons at Various Unbunched Pulse Widths

Figure No.	Particle	Particle Energy MeV	Average Beam Current (μa)	Chopper Amplitude	Unbunched Pulse Width (ns)	Pulse Width (ns) FWHM		Peak Pulse Current (μA)	
						Scope	T of F	Scope	Calculated
2	Proton	6	6	20	45	1.7	1.5	960	1600
3	Proton	6	3.2	40	25	1.5	1.0	740	1280
4	Proton	6	2.0	60	18	1.6	0.8	440	915
5	Deuteron	6	8.5	20	45	2.4	2.0	960	1700
6	Deuteron	6	5.0	40	25	2.4	1.9	740	1065
7	Deuteron	6	2.3	80	14	2.0	1.6	360	591

SECTION 1.5.0

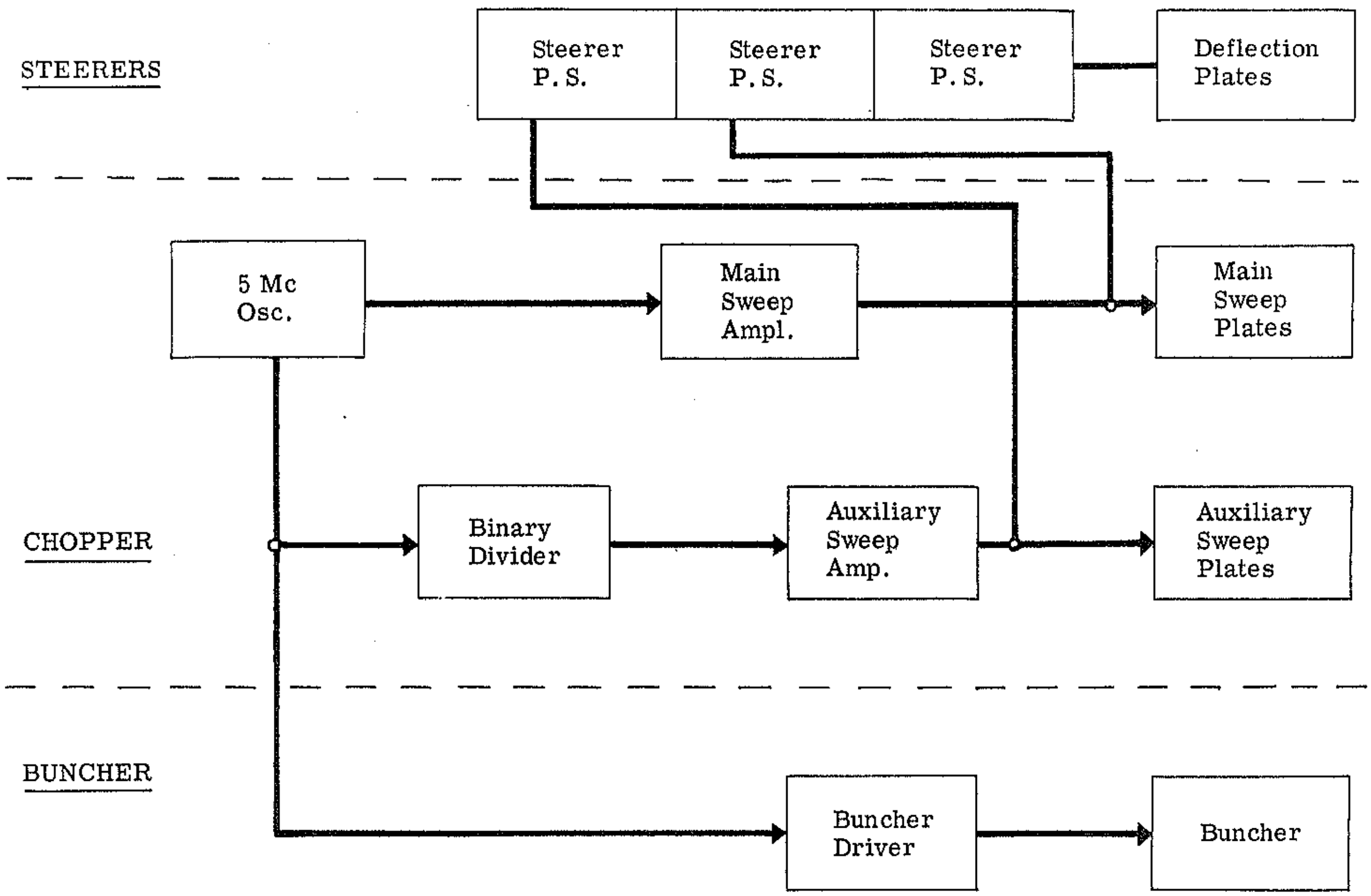


Figure 1 - Pre-acceleration Nanosecond Pulsing System

SECTION 5.3.0

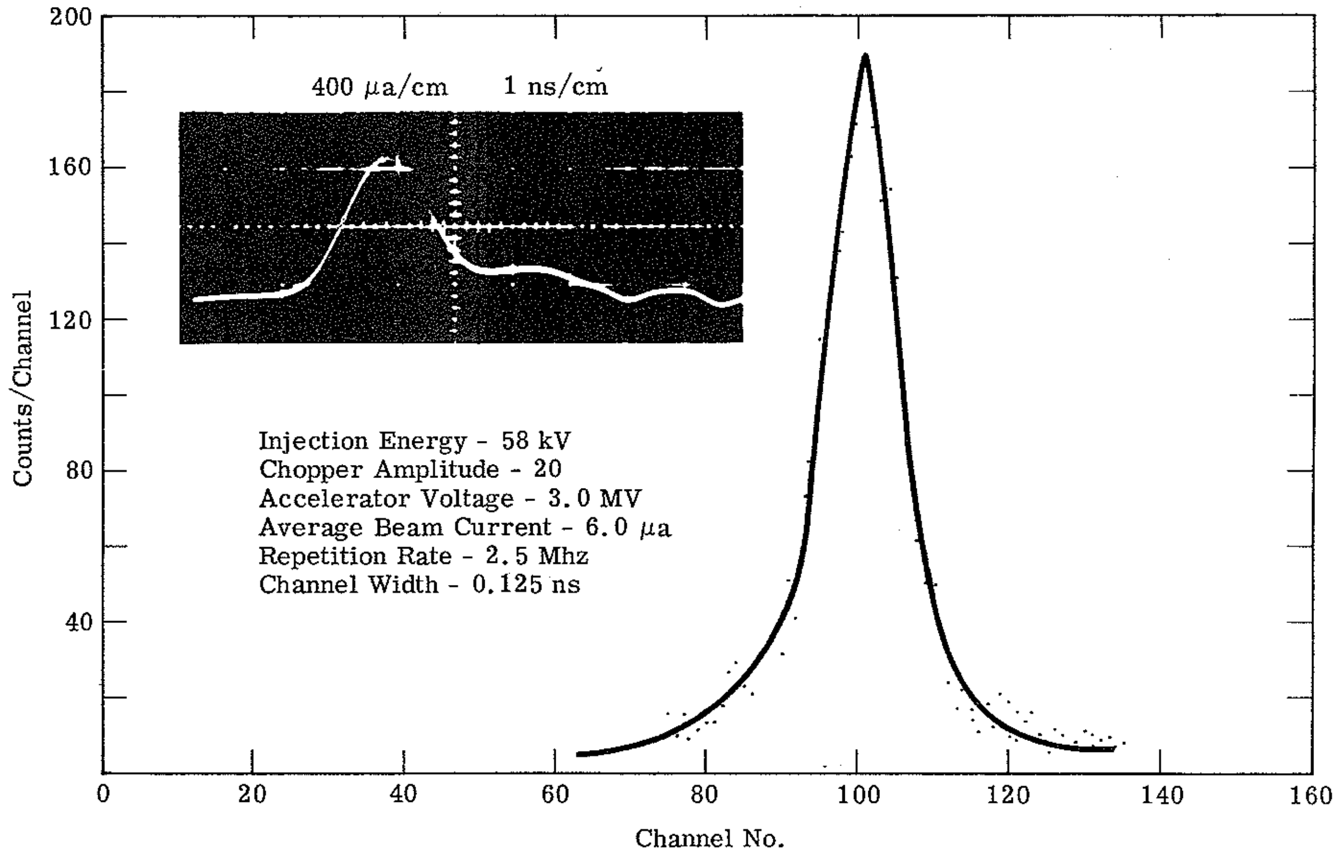


Figure 2 - Analyzed Proton Beam

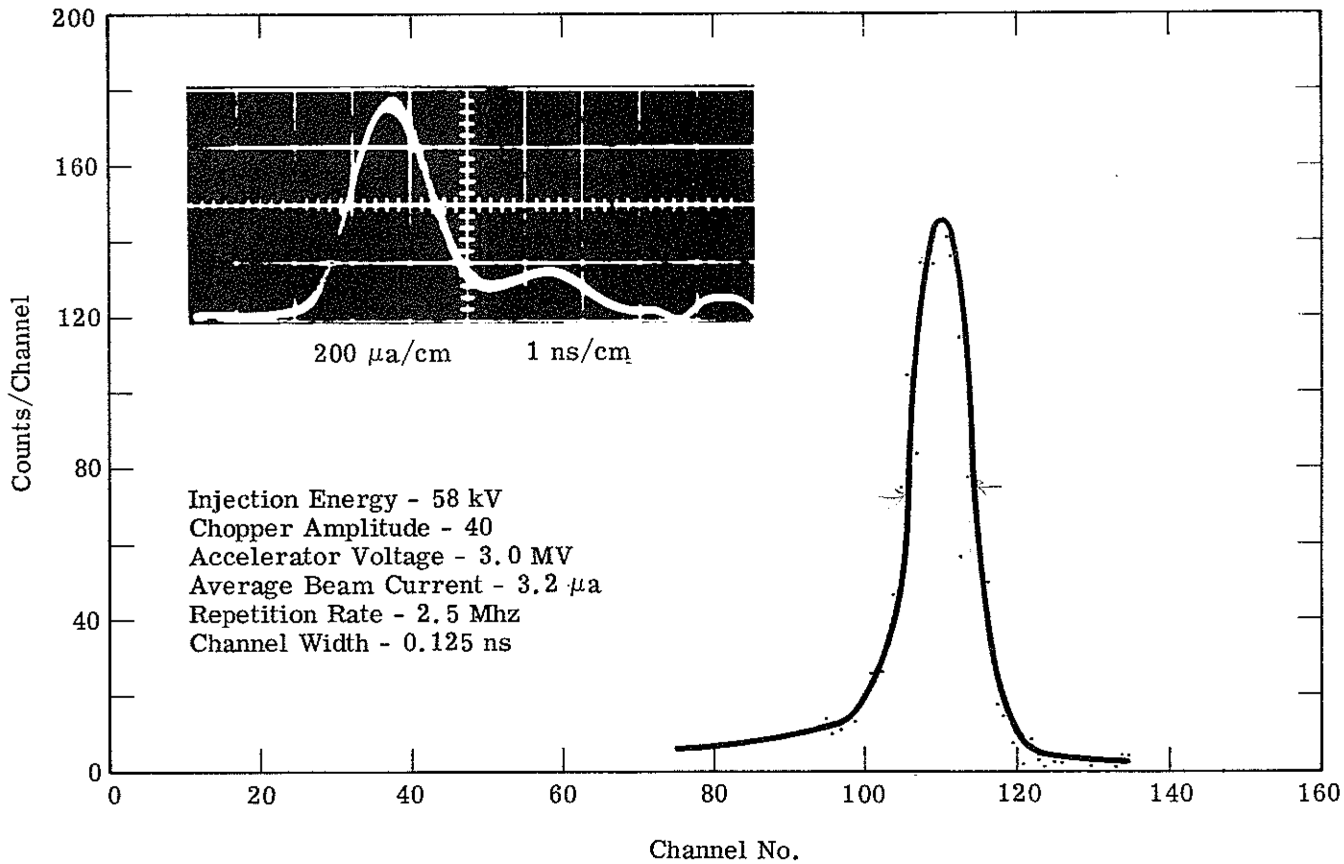


Figure 3 - Analyzed Proton Beam

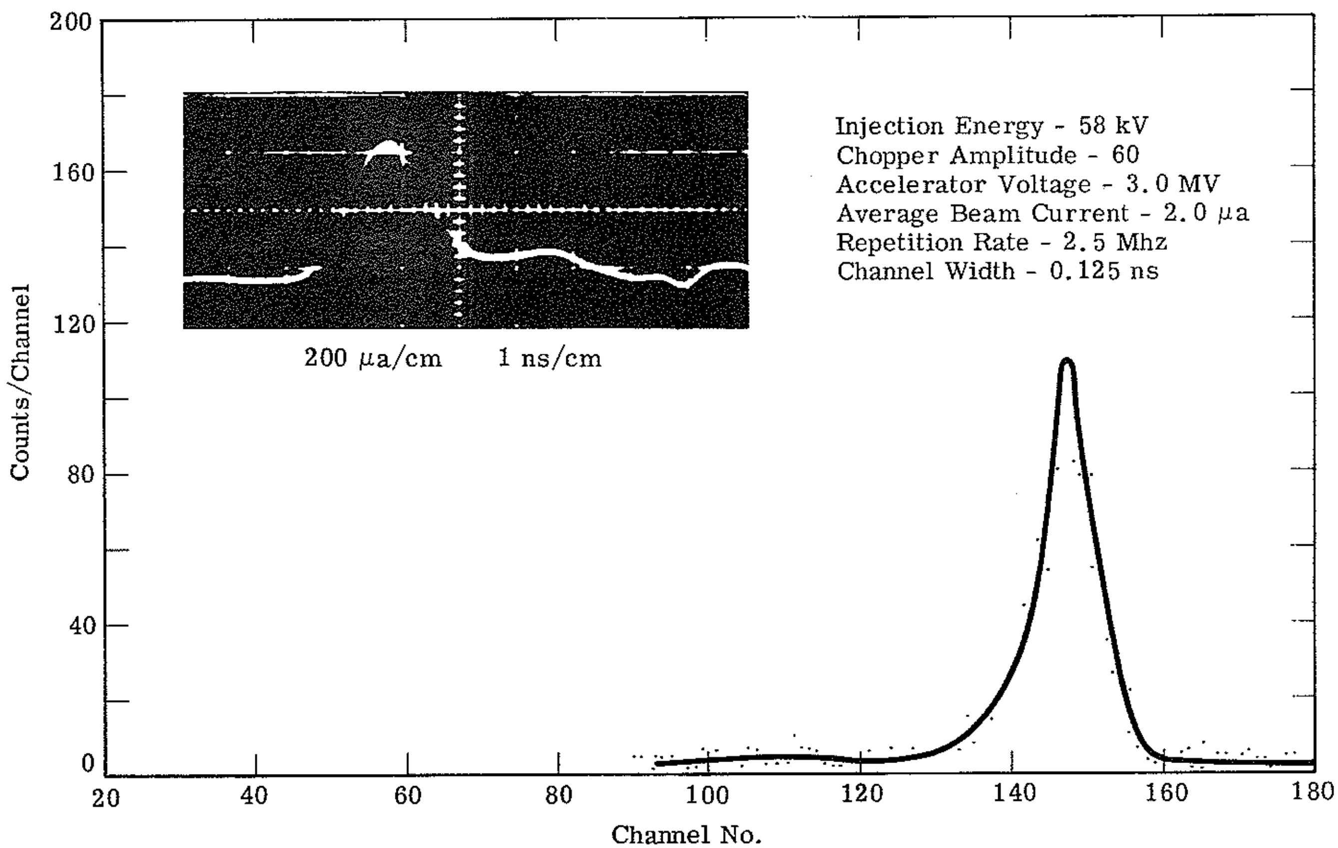


Figure 4 - Analyzed Proton Beam

SECTION 1.5.0

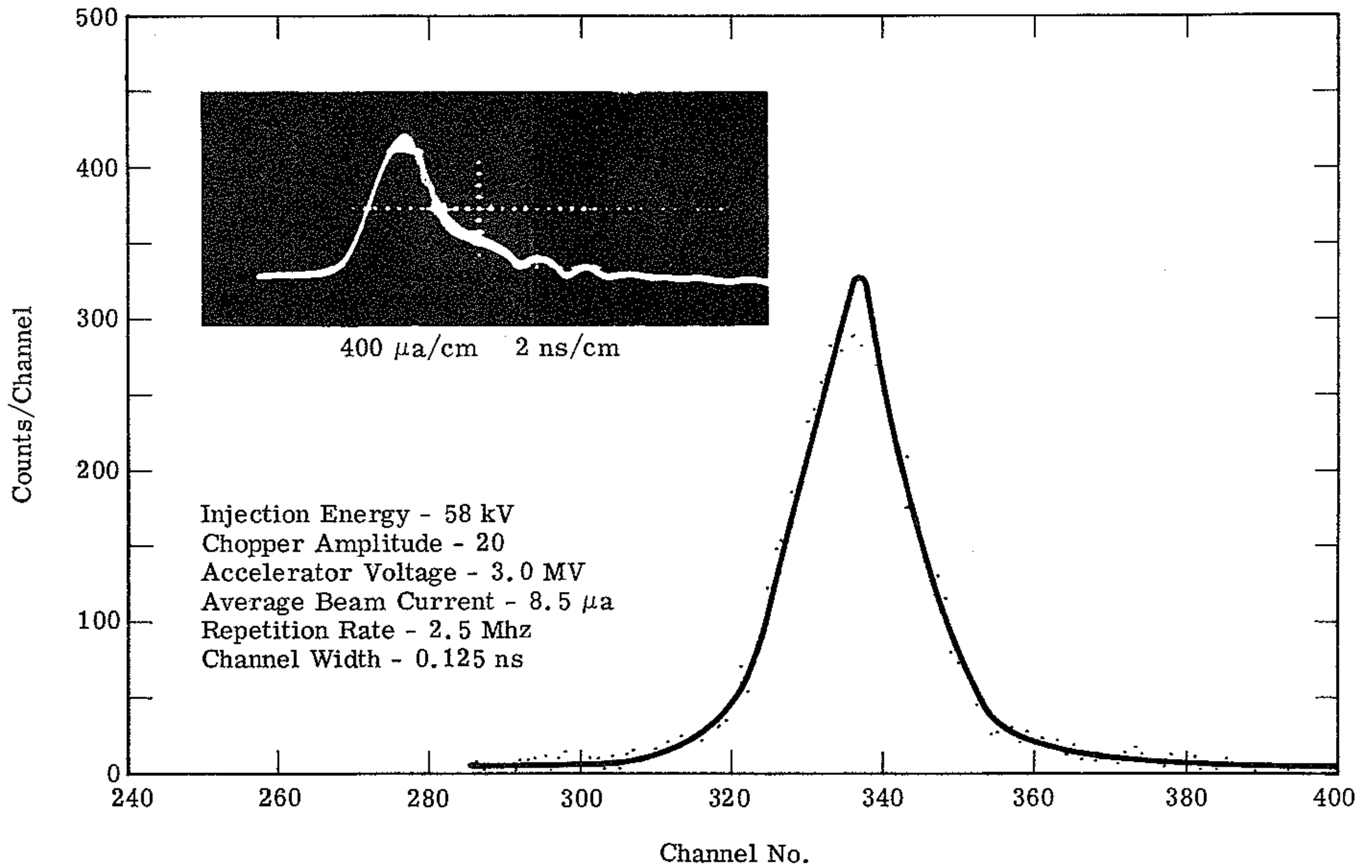


Figure 5 - Analyzed Deuteron Beam

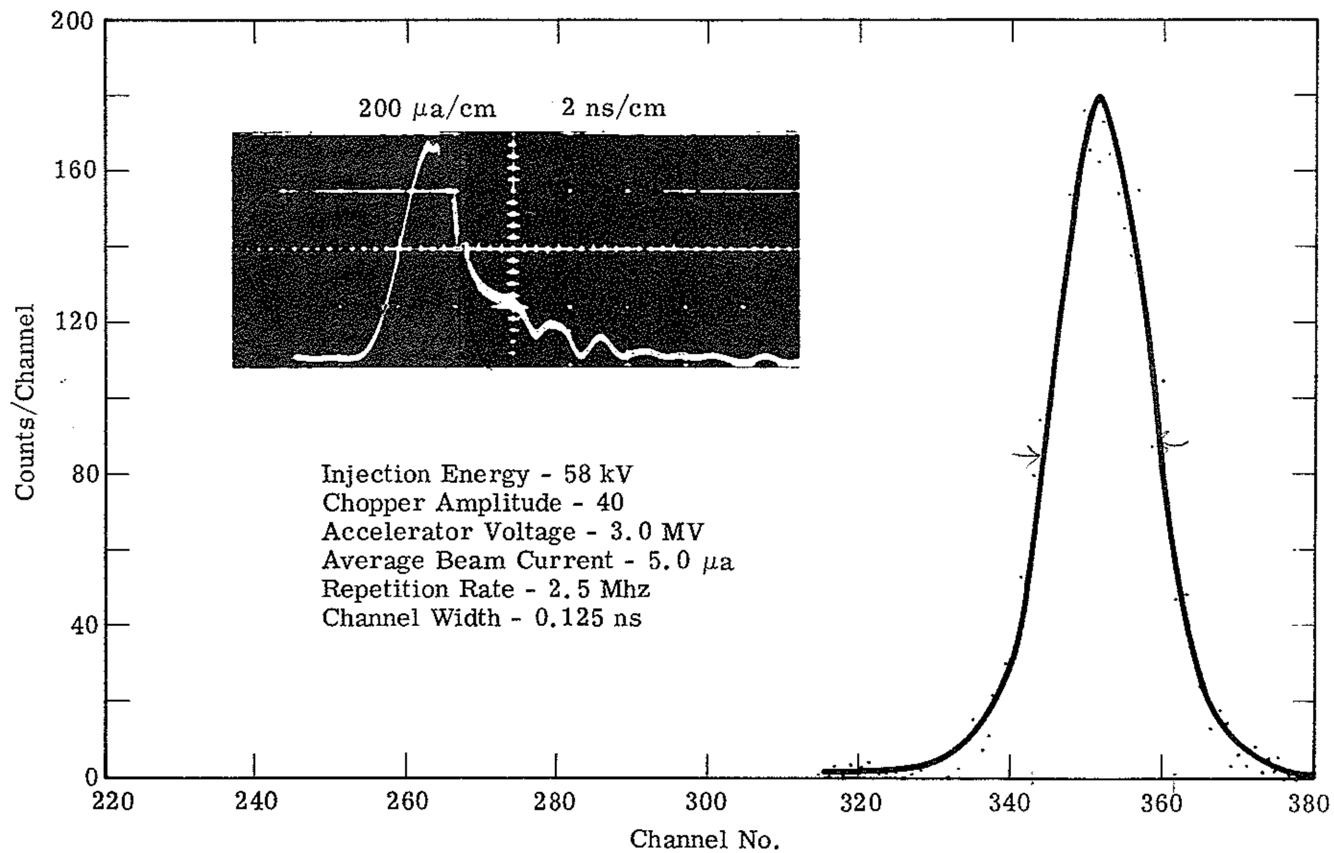


Figure 6 - Analyzed Deuteron Beam

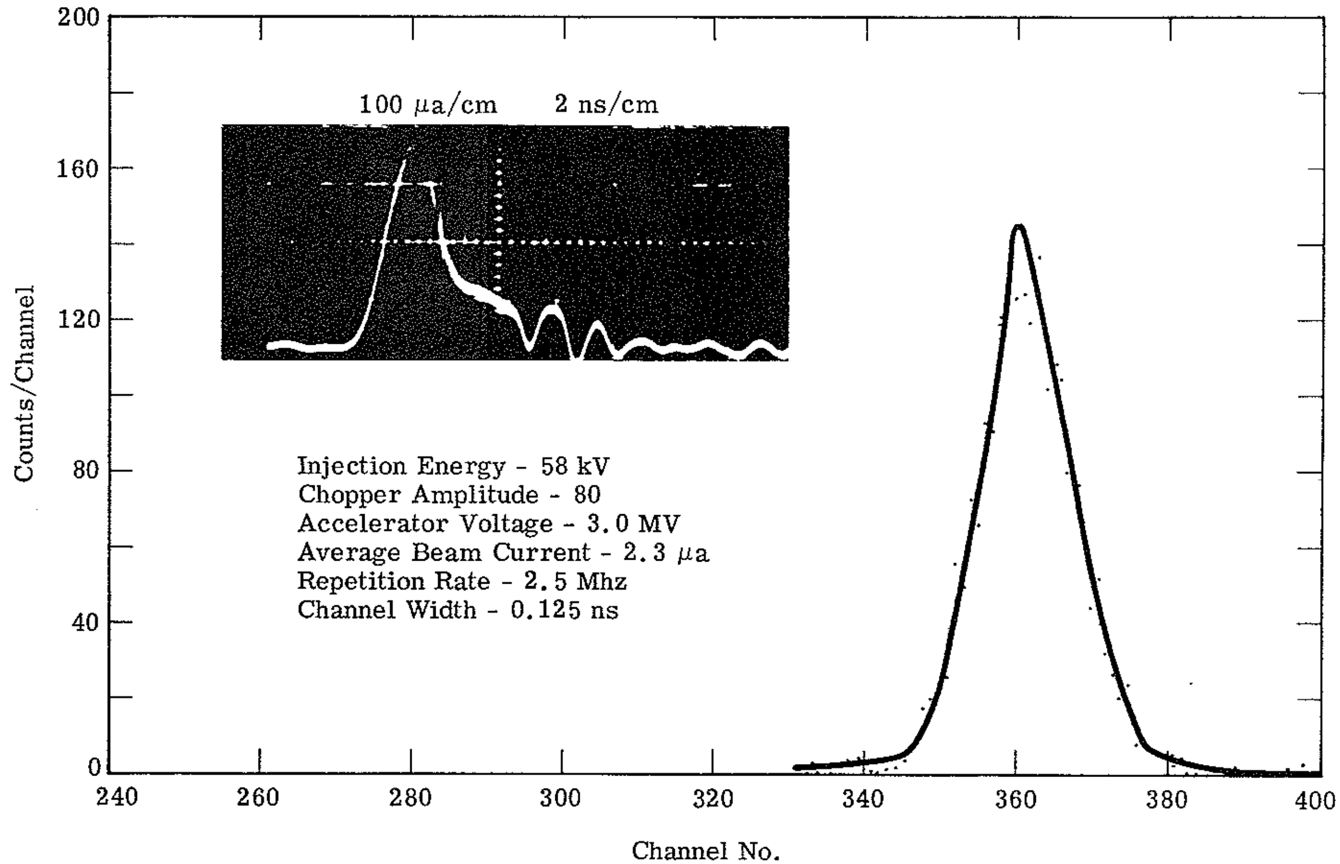
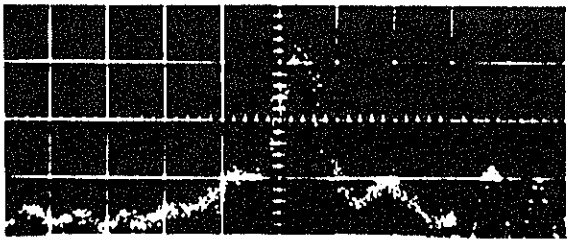
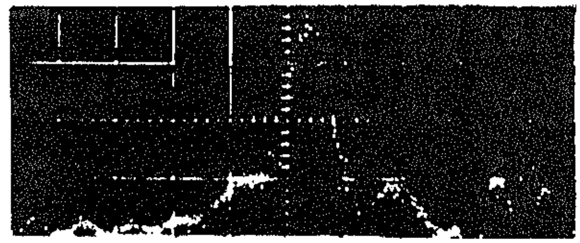


Figure 7 - Analyzed Deuteron Beam



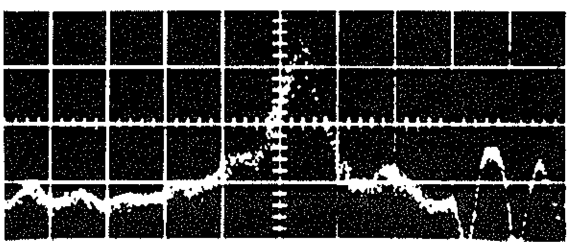
ORTEC TARGET

Chopper - 20 μa
Buncher - 19 μa and 0.7 kV
3 MV - 0.34 μa (target) - 0.30 μa (Faraday cup)
Extraction - 57 kV
Bias - 0 Vdc
2 ns 2 MV (scope)



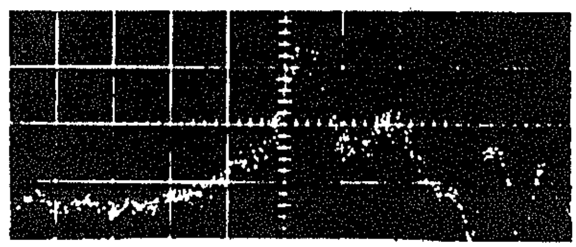
ORTEC TARGET

Chopper - 20 μa
Buncher - 19 μa and 0.7 kV
3 MV - 0.36 μa (target) - 0.35 μa (Faraday cup)
Extraction - 57 kV
Bias - -300 Vdc
2 ns 2 MV (scope)



ORTEC TARGET

Chopper - 20 μa
Buncher - 20 μa and 0.75 kV
3 MV - 0.26 μa (target) - 0.26 μa (Faraday cup)
Extraction - 57 kV
Bias - 0 Vdc
Target - +300 Vdc
2 ns 2 MV (scope)

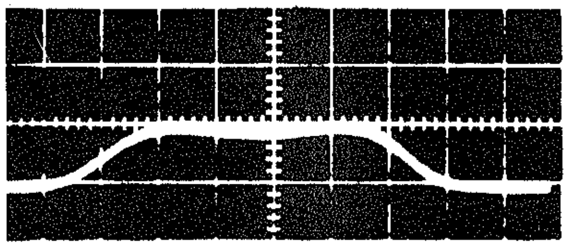


ORTEC TARGET

Chopper - 20 μa
Buncher - 19 μa and 0.7 kV
3 MV - 0.43 μa (target) - 0.27 μa (Faraday cup)
Extraction - 57 kV
Bias - +300 Vdc
2 ns 2 MV (scope)

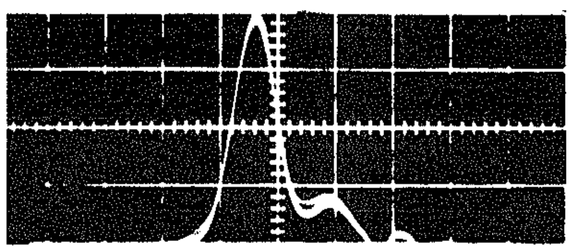
Figure 8

Chopped Ion Beam



10 ns/cm 2 MV/cm

Chopped and Bunched Ion Beam



2 ns/cm 10 MV/cm

Figure 9

SECTION 1.5.0

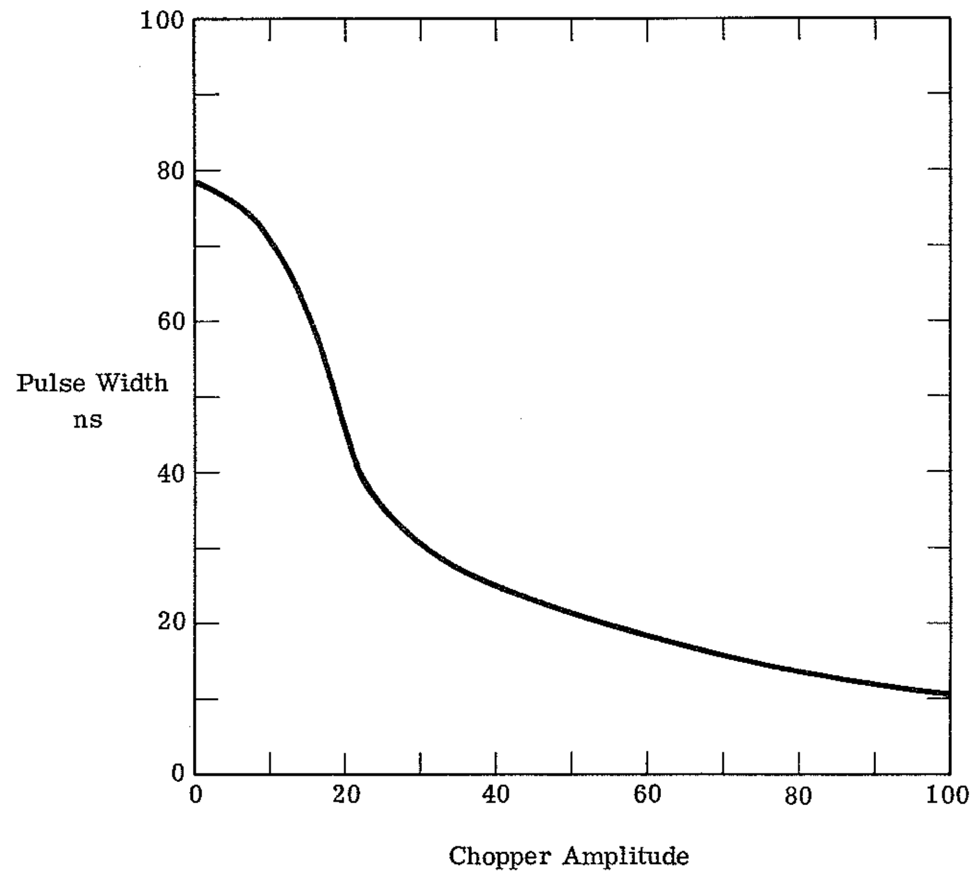


Figure 10 - Unbunched Pulse Width (approx.) vs. Chopper Amplitude - 58 kV protons

1.5.1 Hardware Description:

The pulsing hardware includes ion beam steerers, chopper, and buncher as basic sub-systems as shown in Figure I.

The electrostatic ion beam steerers used in conjunction with the inflection magnet will provide the necessary beam positioning within the low energy extension for maximum transmission through the buncher and the tandem accelerator.

Beam chopping will be accomplished by sweeping the beam across the face of an aperture at the buncher using a set of main and auxiliary sweep plates. The main sweep plates will be driven at the basic sweep frequency and the auxiliary plates will be driven at 1/1, 1/2, 1/4, 1/8, 1/16 and 1/32 of the basic sweep frequency.

A klystron type buncher will be driven at the basic sweep frequency.

1.5.2 Back-up Data:

Tests were conducted on an FN accelerator with a diode ion source and analyzing magnet for the performance of the klystron buncher. The coaxial targets of HVE and ORTEC design were used during the tests with a Tektronix type 545 oscillscope, a type 1S1 sampling preamp and time-of-flight equipment being used for pulse measurements.

Typical results of the tests are shown in Figures 2 to 7 and a comparison of those results is shown in Table I for pulse width and peak pulse current at different chopped pulse widths of protons and deuterons using coaxial target and time-of-flight methods of measurement. The HVE coaxial target results are shown on the oscilloscope pictures of Figures 2 to 7; Figure 8 shows the ORTEC coaxial target. It can be seen that both targets introduce forms of a reflected pulse to the original pulse. This is most likely due to an impedance mis-match at the target. The reflected pulse when added to the original pulse will increase the pulse width measurements (FWHM). This can be observed in comparing the scope and time of flight pulse width (FWHM). Thus, the coaxial target is virtually useless for measuring pulse widths below 1.5 nsec and the accuracy of measurement begins to suffer below 2nsec. The ringing observed on the oscilloscope with the pulse, was also observed with no beam to the target, and we therefore must assume that the ringing was an inherent part of the coaxial target and oscilloscope system.

The observation of peak pulse currents in Table I shows that losses in the coaxial target and oscilloscope system are considerable compared to the calculated value for the time-of-flight method.

Therefore, the time of flight method should be used for the determination of pulse width (FWHM) and peak pulse current with the average beam current being measured in a biased faraday cup.

Typical bunched and unbunched pulses are shown in Figure 9. The bunched pulse has a width of 1.6 nsec and peak pulse current of 800μA by scope measurements. The unbunched pulse has a width of 52 nsec and a peak pulse current of 40μA. These pulses were at a repetition rate of 2.5 MC. Figure 10 shows the unbunched pulse width as a function of chopper amplitude.

1.6.0 Injector Controls:

Operational controls for the Diode ion source startup are provided locally (at the injector) as are a means of varying all pertinent source power supplies at the injector. Normal operation, after startup, will be performed from the main control room console, utilizing a television presentation of a meter panel mounted in the 80 kilovolt high potential cabinet, in conjunction with a control panel which remotely runs servo driven lucite rods to vary source power supply parameters. Servo motors are located in the mounting base of the high potential cabinet.

Metering is provided at the main console for reading such necessary parameters as -- the beam current intercepted by the magnet chamber, low-energy Faraday cup beam current, Einzel lens voltage, steerer voltage, and inflection magnet coil current. Interlocks will be provided to shut down critical power supplies in the event of vacuum, power, or cooling water failure.

2.0.0 Tandem Van de Graaff Accelerator:

A unique "Tee" configuration is proposed which combines well proven components with the most recent developments in high voltage engineering techniques in an efficient, compact design. Overall system advantages include effective isolation of the high potential generating section from the critical area of controlled voltage gradient along the acceleration tubes, expandable current capacity, and compact system packaging. Installation of this equipment in facilities previously considered only suitable for much lower energy machines is thereby possible. Energy conversion from the A. C. mains power to high potential D. C. is performed with great efficiency thereby reducing operating costs and maintenance problems.

COMPONENT LIFETIMES:

Charging Belt: The expected belt life is in excess of 5000 hours under normal use and operating conditions. Life data on belts used under similar conditions has indicated a variation from between 500 hours to greater than 5000 hours.

The shorter belt lives have occurred either from improper installation or improper drying. Improper installation has been a) improper belt alignment, b) poorly adjusted charging and/or collecting screens, c) low belt tension. We have rarely had a belt failure due to moisture in machines which are equipped with a recirculation and dryer system.

Accelerator Tubes: The acceleration tubes will be constructed with stainless steel electrodes and the latest high gradient techniques; we expect their life to be in excess of 10,000 hours under normal conditions. Extensive life data on such tubes is not available but our expectations and confidence level are reflected in the change of our standard warranty from 1000 hours to 3000 hours.

The ability of stainless steel electrode acceleration tubes to go to higher voltage is probably due to their ability to be conditioned to higher voltage without permanent damage by transfer of material from the electrodes to the glass insulators.[a] This metal transfer has been the usual limit with aluminum electrode acceleration tubes. Figure I illustrates the basic conservatism of this design based on previous reliable data.

[a] The addition of stainless steel electrode tubes in the low energy end of the Pittsburgh neutral negative machine eliminated a metal transfer problem which was encountered with the aluminum electrode tubes. These low energy tubes were subjected to considerable ion beam and secondary electron bombardment. Based upon this result and additional experimental results obtained in our own plant on other machines we feel that this type of tube is also vastly superior for high current applications.

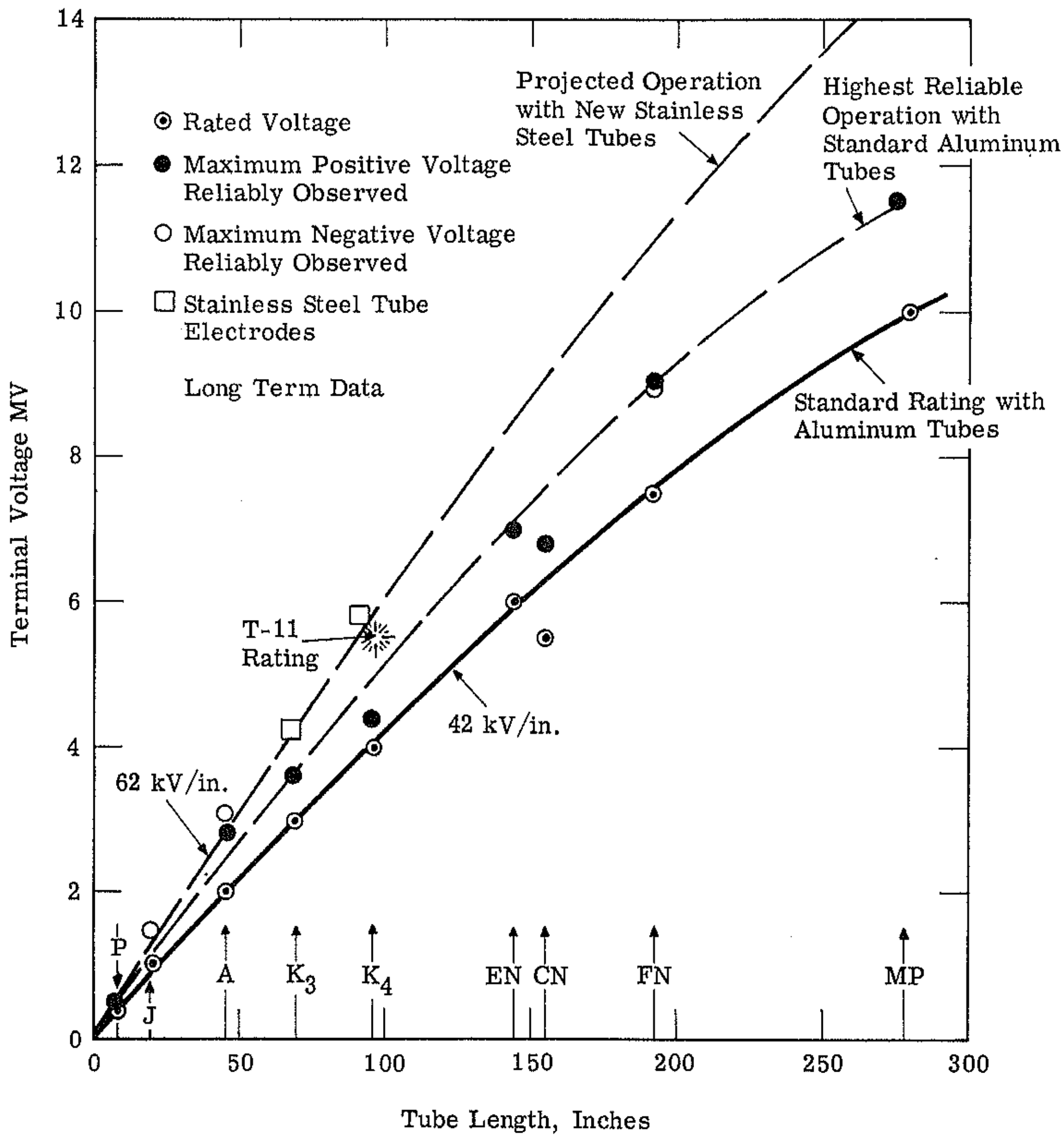


Figure 1 Terminal Voltage vs. Active Tube Length for HVE Accelerators

2.1.0 Terminal high potential is generated by the mechanical transfer of electrostatic charge, on a moving dielectric belt, from ground to the insulated terminal enclosure. The "Van de Graaff" generator is part of a support column which acts as a compressive load bearing structure in the center of the pressure vessel. For the quoted specifications of this machine, a single belt charging system is provided which, at a terminal potential of 5.5 million volts has a 1.5 milliampere current capability. Support column design is such that two additional belt charging systems may be readily added without structural modifications. This allows economical initial procurement and operation, while permitting future expansion to 5.5 million volts. 4.5 milliamperes, by inexpensive component additions. In the interests of operating within existing annual support budgets, this expandable feature is extremely desirable, since it provides more than adequate power supply capacity to utilize existing negative ion injector and tandem technology without incurring disproportionate expense for power consumption and maintenance.

Gradient control down the support column is maintained by a series of specially designed, high quality, resistors in conjunction with bars for field control at the belt surface. Column structure is an 80-inch long epoxy laminate of glass insulators and metal equipotential planes which in turn support field terminating equipotential metal hoops.

Primary mechanical power for the charging system is provided by a 440 volt, three phase, drive motor, which is nominally rated at 30 horsepower and drives the lower belt pulley. The upper belt pulley, in the high potential terminal, is a 400 cycle per second inverted alternator rated at 3000 watts. Normal power required for present tandem operations is adequately provided by this single unit; in the event of additional belt charge systems being added in the future, it is interesting to note that the ultimate available terminal A.C. power is 9000. watts.

Charging of the belt is accomplished by means of a specially designed metal screen on the uprun side which is operated by a 50 kilovolt, highly stable, current regulated, power supply. The power supply and regulator are located external to the accelerator pressure vessel for accessibility and ease of maintenance.

2.2.0 Ion Beam Acceleration Tube System:

The multisectioned acceleration tubes are constructed from annular, 14-inch outside diameter, glass insulators and #304 Stainless Steel electrodes laminated with a low vapor pressure adhesive.

The low energy acceleration tube, at the injector end of the machine, has electrodes which are specially shaped and inclined at small angles from a plane normal to the beam axis, and a gridded entrance lens[5]. The grid serves to terminate the tube entrance field hence eliminating the lens effect inherent in the fringing field. This allows the strength of an external lens to be varied independently of the accelerator terminal potential.

Since negative ions are relatively "fragile", and require good vacuums to prevent stripping during acceleration, the low energy tube is baffled from the stripper gas flow and hence operates at vacuum levels of approximately 10^{-6} Torr. Experience has shown that under conditions of very good operating vacuum levels, a larger number of electrons are formed and accelerated, from the tube electrodes, causing increased instability and loading at high voltage gradients.

A computor-determined arrangement of inclined electrodes with varying angles is used to transport the negative ion beam while deflecting and eliminating the electron beam loading in the tube.

The high-energy beam tube, for accelerating the positive ion beam after charge stripping, is similar in construction to the low energy tube.

Both tubes have insulating lengths of 96 inches and use "snap-around" epoxy encapsulated highly stable resistors for establishing a uniform voltage gradient along their lengths. Equipotential metal rings are mounted on each "snap-around" resistor to uniformly terminate the electrostatic field lines in the insulating gap between the acceleration tubes and the tank wall.

Tube system mechanical support is accomplished at both ends by the pressure vessel walls and in the center by the support column which houses the high potential generating system.

2.3.0 High Potential Terminal Enclosure:

A smoothly polished stainless steel terminal enclosure acts as an equipotential surface surrounding the high potential junction of the acceleration tubes and the voltage generator support column. Enclosed within this 54" diameter terminal is the alternator, or upper charging belt pulley, the stripper box, stripper gas supply with leak, and the foil advancing and positioning mechanism. Ports are provided on the stripping box for future addition of two 250 liter/second ion pumps.

The stripper box includes a gas stripper tube permanently mounted on the beam axis and a chain feed mechanism containing 64 stripper foil holders which may be singly positioned with great accuracy on the beam axis. The gas stripper aperture is adequate to permit transmission of high intensity beams, using foils, by simply eliminating the stripper gas flow and positioning a foil on the beam axis after the stripper tube exist. Foils provided will be 10 μ-gram/cm^2 carbon.

The foil stripper has the capability of holding 64 foils and four open positions. For every sixteen foils there is one open position. The open position is used in conjunction with the gas stripper operation. The time to place a new foil in position is 10 seconds, and the maximum time required to shift from foil to gas operation is 160 seconds. The foils may only be moved in one direction.

Carbon foils will be provided with the assembly for use in meeting proton and deuteron specifications.

An estimate of the gas flow in the stripper canal during equilibrium conditions at 4.0 MeV is 60 atmos-cc/hr for proton beams.

Gas flows required for equilibrium with heavy ion beams would be considerably lower. The high energy acceleration tube has more than adequate pumping speed to handle these gas flow rates.

Access to and service of the terminal components is possible, via an access hatchway, without the removal of major portions of the pressure vessel, the accelerator tubes, or the support column. All components in the High Potential Terminal Enclosure have a minimum working life between service of 500 hours, with the exception of the foils whose life is beam level (and ion species) dependent.

2.4.0 Insulating Gas Pressure Vessel:

The entire high potential generator and accelerator system is housed in a steel pressure vessel constructed of intersecting cylindrical sections, which is rated at 120 PSIG, and is provided with access hatchways for entrance and component removal or maintenance. All routine servicing, including the replacement of the accelerator tubes, is accomplished by means of access ports, without the removal of major portions of the pressure vessel. The mechanism for the opening and closing of the entrance ports of the pressure vessel and for removal and replacement of accelerator tubes and major terminal components is provided. A series of standard size portholes are provided for the mounting of various accessory equipment such as the generating voltmeter, corona points, and viewing ports. The pressure vessel will be manufactured and tested in accordance with the Code of Regulations for Unfired Pressure Vessels of the American Society of Mechanical Engineers.

A large port is provided for the purpose of evacuating the tank prior to pressurizing to 100 PSIG with Sulphur-Hexafluoride insulating gas. Internal cooling is accomplished by means of convection of the insulating gas through coils, which are mounted in the top of the pressure vessel, and cooled by chilled water. Pressure vessel weight is 25,000 pounds without internal components and gas volume required is 1400 cubic feet. Internal contour of the pressure vessel is shaped and uniformly smooth in accordance with good high voltage electrostatic engineering principles.

Sulphur-Hexafluoride is used due to its superior relative dielectric strength and its excellent thermal transfer characteristics. By operating at lower tank pressures, transfer times are substantially reduced representing a savings of facility operating time. Pure Sulphur-Hexafluoride is non-toxic and non-corrosive. An extensive investigation of its properties was made at Chalk River[6] prior to their conversion to Sulphur-Hexafluoride as the insulating gas for their Model MP Tandem Van de Graaff accelerator.

2.5.0 Insulating Gas Handling System:

A fast gas-handling system, for rapid transfer of Sulphur-Hexafluoride from the pressure vessel to storage tank is provided and includes a compressor, vacuum pump, recirculator, dryer, storage tank, humidity gauges, and all necessary valves, piping and electrical wiring. Gas lines of 4 inches in diameter are used wherever possible. The total turn-around time for gas evacuation of the accelerator, pumping, and subsequent filling may be accomplished in less than 8 hours as shown in figure I. During a normal complete transfer from the pressure vessel to the storage tanks, no more than 50 cubic feet NTP of Sulphur-Hexafluoride will be lost. The Sulphur-Hexafluoride will be kept in the gaseous phase at all times. A re-circulating system is provided which is capable of drying the gas during normal accelerator operation. The storage tank will be mounted inside on an overhead wall of the accelerator room, and the remaining gas transfer equipment will be mounted in such a way as to occupy a minimum amount of floor space.

2.5.1 Component Description:

A tandem type compressor, of non-lubricated construction, and having a sealed housing surrounding the stuffing box is used. Delivery capacity will be approximately 80 cubic feet per minute with a maximum discharge pressure of 300 PSIG. The compressor utilizes a 30 HP motor and weights approximately 5400 pounds.

A steel storage tank 8 feet in diameter, 14.3 feet long, and having a volume of 620 cubic feet will be used. The storage tank has a pressure rating of 300 PSIG and conforms to the ASME code for unfired pressure vessels. As an assembly the tank will include pressure and temperature gauges as well as an alarm (horn) system which is activated by the existence of an over pressure condition.

Two paper cartridge type filters are included; one before the compressor and one at the accelerator pressure vessel. Each filter will have two pressure gauges.

A 5 HP vacuum pump equipped with a surge tank will be used to evacuate the last atmosphere of Sulphur-Hexafluoride or air during the transfer cycle.

The gas drying and re-circulating sub-system includes a 25 cubic feet per minute positive displacement blower and a dual cylinder (parallel-connected) chemical dryer, which contains 150 pounds of alumina. The dryer contains reactivation heaters and a pre-heater. A poro-stone filter, and a paper cartridge filter, are included in the re-circulator closed loop system.

All valves will be of steel ball type construction with double packed stem seals.

2.5.2 EQUIPMENT SPECIFICATION

OF

SF_6 GAS TRANSFER FOR A T-8/50

PHYSICAL DATA

STORAGE TANK

Volume (Cu. Ft.)	620
Normal Storage Pressure (at 70° F PSIG)	206 PSIG
Max. Pressure (PSIG)	300
Weight (lbs) w/o Gas	17,200 lbs.
Approx. Tank Dimensions (Dia. x Lg.)	8' x 14.3'

Note: 250 PSIG for 120 PSIG SF_6 Charge in Accel.
206 " " 90 " " " " "

COMPRESSOR

Horsepower	30 HP
Delivery Capacity (Approx.) (CFM)	80 CFM
Discharge Pressure (Max)	300 PSIG
Type of Construction	Tandem Non-Lubricated
Special Extra.	Sealed Housing Surrounding Stuffing Box
Approx Weight (lbs)	5400
*Approx Dimensions (W, Lg, H)	3'6" x 13'9" x 5'8"

*Note also need extra. on Lg. 4'2" for removal of pistons and rods.

PHYSICAL DATA - cont'd

SF_6 GAS

SF_6 Charge/Accel (lbs) 90 PSIG	4158#
SF_6 Storage Capacity (lbs) for 90 PSIG Accel Charge	4573#
Max Storage Capacity (lbs) for 120 PSIG Accel Charge	6100#

COOLING WATER REQUIREMENTS

Compressor (GPM) at 85°F (Approx)	7-1/2	Between these limits
or		
" " at 50°F "	40	
Vac. Pump. (GPM) at 85°F	1/4	

PERFORMANCE DATA

Evacuate the Accel. (1 ATM. to 7.5 mm Hg)	1.1 hrs
Accel. Charge Time	1.1 hrs
Accel Pump-out Time (to approx 7.6 mm Hg)	3.3 hrs
Air Admittance for Vac. to 1 ATM	.5 hrs

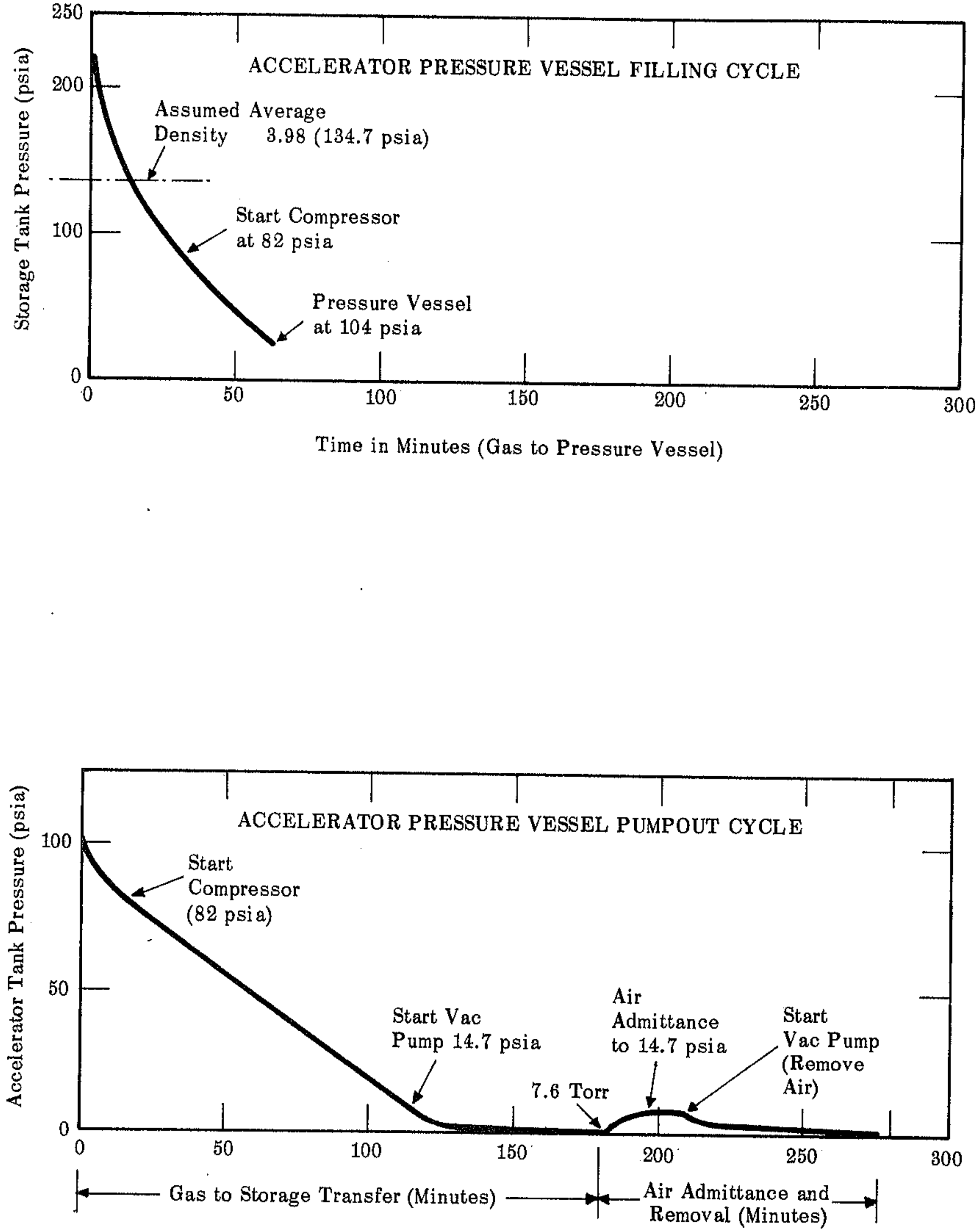


Figure 1. – Transfer Cycle of the Gas Handling System

2.6.0 Accelerator Vacuum Systems:

Identical high speed vacuum systems are used at both the low and high energy ends of the accelerator and each consists of a 6" NRC cold capped oil diffusion pump equipped with mechanically refrigerated baffles, of modern design, such that back-streaming and creeping of diffusion pump fluids into the accelerator tubes or extensions will be effectively eliminated. Each diffusion pump is provided with two gate valves: one which isolates the accelerator tube and is automatically operated by vacuum or power failure; and one manually operated, which isolates the diffusion pump. A by-pass roughing line is provided at each station. These pump systems are compactly and efficiently housed, together with all necessary support equipment and interlocks, directly at each end of the pressure vessel. Interlocked functions include vacuum, electrical power, and cooling water failure. All vacuum gauges and metering will be such as to provide emergency shutdown of the entire accelerator in case of vacuum or power failure.

Liquid nitrogen or liquid air traps are not used for the operation of the accelerator at any rated voltage or current. The vacuum systems will provide a static (accelerator or injector not in operation) vacuum levels of 1×10^{-6} Torr or better. Zeolite molecular sorbent baffles are not considered since their manufacturer does not recommend their use in frequently cycled systems.

3.0.0 Post Acceleration Ion Beam Transport System:

This section describes the thoroughly integrated ion beam analyzing and transport system provided with the accelerator facility. Features which occur uniformly throughout the system are listed here to avoid needless repetition in following sections.

3.0.1 The basic drift tubes are all made of stainless steel and have a nominal 4-inch inside diameter. In those areas where it is necessary to reduce the drift tube diameter, in order to connect with other components, the 4-inch inside diameter will be re-established as soon as it is practical to do so.

3.0.2 All controls and indicators for the magnet power supplies, vacuum gauges, beam monitors, etc., are located at the main control console and all necessary cables are supplied with the equipment.

3.0.3 Computer calculations of the anticipated beam profile have been performed by High Voltage Engineering Corporation and are summarized in Table I. These calculations are used to determine the correct location of the analyzing magnet, the switching magnet, all quadrupole lenses, and other active optical elements. Target locations specified by the Ohio University Faculty have been used as the basis for all calculations.

3.0.4 Final location of the analyzing magnet and the switching magnet may be adjusted by the Ohio University Faculty and High Voltage Engineering Corporation, in conference, based on the optics calculations.

3.0.5 Minor items of standard vacuum equipment such as "O-rings" are not itemized, but are included wherever necessary.

3.0.6 Quick opening high-vacuum couplings, B-VAC-425-000 Series, are used in all joints where the vacuum system is expected to be opened frequently.

3.0.7 All components supplied are of the highest quality and are guaranteed to be of new manufacture.

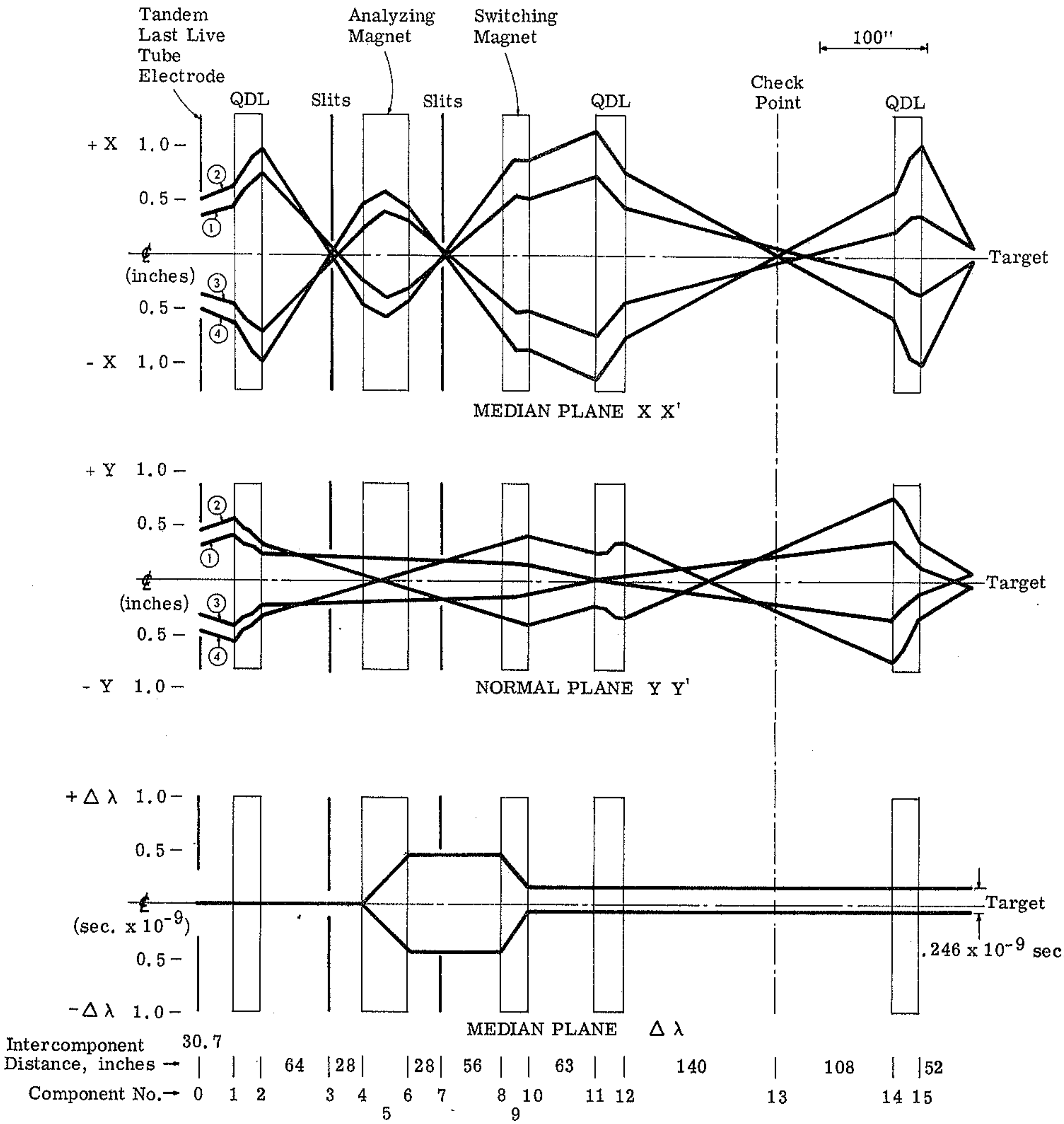


Figure 1 +45° Leg, 5 MeV Pulsed Proton Beam

3.1.0 Beam Line Components listed in the order in which they are supplied starting from the accelerator tank base is as follows:

3.1.1 4" bellows stem sealed, remotely operated, automatic gate valve, (High Voltage Engineering type B-VAC-97) which may be closed by a suitable external signal from the vacuum measurement system. This gate valve eliminates stem sealing "dynamic" O-rings and the usual gas load, or burst, encountered with such valves. Design simplicity and the absence of constricting mechanical fits, contribute to an outstandingly low leak rate of less than 5×10^{-9} Torr-liters/second. The valve is vacuum tight in either direction against atmospheric pressure. Viton plate and bonnet seals are used. Throughput is a full 4 inches. Operation of the automatic feature is by means of an electrically actuated air solenoid which in turn pressurizes the main air cylinder with 75-100 p.s.i. of air to close the valve.

3.1.2 A remotely operated, air actuated, ion beam stop and Faraday Cup, which may be inserted into the beam path from the main control console, is included. This allows monitoring of the beam at the exit of the accelerator prior to entrance into the first active optical element of the beam handling system and beam stopping in the event of difficulty further out in the transport hardware.

3.1.3 A 4-inch by 2-inch "Reducing Tee", with the 2-inch port blanked off, is included to facilitate future addition of a beam profile monitor (scanner) head.

3.1.4 The first magnetic quadrupole doublet lens is provided complete with mounting frame, for the 42-inch beam centerline height, and is located close to the high energy baseplate of the accelerator. The Model M-321, which has an effective (tip-to-tip) aperture of 3.06 inches, and an overall length of 30 inches will focus an ion beam of Mass Energy Product 60, without saturation, at a doublet focal length of 60 inches.

Each singlet yoke is fabricated from low-carbon steel, with the saddles of the quadrupole poles accurately machined by precision horizontal jig boring. This technique assures accuracy of pole alignment not easily achieved in other quadrupoles. Typically, the axial alignment, pole gap uniformity, and pole parallelism are within $\pm$ .001 inch. A generous yoke structure precludes pole root saturation.

The poles are made from centerless ground low-carbon steel and are fastened to the yoke saddle by holding screws. Both pole length and yoke length are precision machined to assure uniformity and pole registration. Diameter of the circular cross-sectioned poles is 1.15 times the tip-to-tip aperture in order to attain a uniform field with minimum harmonic distortion[7].

Coils are constructed of wet-wound epoxy coated copper wire; all insulation is to Class F (155^{o} C) standards. A central water cooled plate dissipates coil losses, permitting reliable operation at maximum rated field gradients. The coils are wrapped with fiber glass tape and impregnated with epoxy resin for protection against damage from normal handling. Coil terminations are in limited access junction boxes. Thermostatic switches are included to prevent coil failure due to cooling water stoppage.

The magnet center and geometric center of each singlet is coincident to within .005 inch which eliminates any need for special magnetic center determination or marking. This is accomplished by using:

Identical number of turns on each coil

Identical current through each coil due to series electrical connections

Coil inter-connections layout such that no unequal portions of a turn are added or lost

Particularly accurate control of poles and air gaps

In the doublet configuration, used in this system, the separation of singlet lens elements (centerline to centerline) may be adjusted at any time for up to 3 inches greater separation than the nominal 1.5 times to pole length, for individual special requirements. Doublet mounting avoids azimuthal displacement (twist) and retains coincident centerlines between elements by means of a precision machined way which accurately locates the beam axis in two planes. Adjusting screws are provided which allow ± 1/2 inch of adjustment for the doublet in all three planes.

The vacuum chamber is stainless steel, 3-inch nominal o.d., and has standard Dependex(R) terminations.

3.1.5 Two 50 ampere 40 volt power supplies, having long and short term current stability better than $\pm 2 \times 10^{-4}$, are used to provide the doublet coil current. These supplies are rated at:

<u>DC Output</u>	0-40 volts at 0-50 amps
<u>Load Regulation</u> The Constant Voltage & Constant Current Load Regulation specifications are given for load current and voltage changes equal to the rating of the supply.	CV -- 0.01% plus 200 μv CC -- 0.02% plus 3 ma
<u>Line Regulation</u> For a change in line voltage from 100 to 130 or 200 to 260 at any output voltage and current within rating.	CV -- 0.01% plus 200μv CC -- 0.02% plus 3 ma
<u>Ripple and Noise</u> At any line voltage and under any load condition within rating.	CV -- 1 mv rms CC -- 30 ma rms
<u>Stability</u> Under constant ambient conditions, total drift for 8 hours following 30 minutes warm-up.	CV -- 0.03% plus 2 mv CC-- 0.03% plus 10 ma
<u>Meters</u>	0-50 v and 0-60 a
Controls	Front Panel Coarse & Fine

These power supplies are constant voltage/constant current with automatic crossover and utilize all silicon solid state circuitry.

3.1.6 The Beam Profile Scanner with remote monitor is capable of scanning a 1.25 inch diameter beam and measuring a minimum total pickup of 10^{-2} microamperes. Power dissipation is such as to be able to be used continuously without damage at the maximum beam power conditions specified in section 6.2.0.

The Beam Profile Monitor is used to measure the current and position of the ion beam. The system includes a driver-display center and scanner head. As many as seven scanner heads may be accommodated with a single control chassis.

The scanner head contains two insulated tungsten-rhenium wires which extend from a resonant cantelever arm and vibrate perpendicular to one another and to the direction of the beam. A signal is generated when the wires interrupt the ion beam. That signal is proportional to the total current and indicates the position of the beam. Each scanner head has a built in silicon field effect transistor pre-amplifier.

The scanner head housing consists of a length of stainless steel tubing welded to a 2" stainless flange which, when clamped to the 2" port of a 2" x 4" reducing "T", forms a vacuum tight assembly. An electromagnet drives the sensor wires at about 15hz. When energized with direct current, the electromagnet retracts and holds the sensor wires out of the beam path.

A palladium contact is actuated as the sensor wires pass through the mechanical center (rest) position and an indicating marker is developed which may be superimposed on the display to locate the center of the scan.

The control indicator chassis contains the following:

1) A 5-inch oscilloscope and electronic switch for simultaneous display of vertical and horizontal scans.

2) The circuitry for holding the scanner sensors out of the beam path.

3) The circuitry for driving the scanner heads.

Seven output connectors are located on the rear of the control chassis so that up to 7 scanners may be accommodated. Only one head may be "scanned" at one time. The remaining 6 scanner wires will be automatically drawn out of the beam path.

Specifications:

Sensor wire:	Tungsten Rhenium .03 diameter
Scan frequency:	15 hz.
Scan Amplitude:	0.4 to 1.25 inches peak-to-peak controllable over range.
Minimum Detectable Beam Current:	10^{-8} ampere
Maximum Beam Current:	500 micro-amperes at 4 million volts with a beam diameter of approximately 0.25 inches
Power used:	117 volts, 50 or 60 hz., 150 watts.

Specifications:

Weight of scanner:	2.5 lbs
Height of scanner above flange:	7 inches
Control Indicator Chassis:	Standard 19" wide rack mounting panel, 8-3/4" high, 15" deep.

3.1.7 A Double Object slit assembly is located at the object point of the 90° analyzing magnet. A self-contained micrometer thimble is built into each slit so that the slit position may be accurately determined to within 0.001 inch. Leakage resistance for the air-cooled slits is greater than 10^{11} ohms. Assembly power dissipation, including the water-cooled aperture located in front of the slits, is 500 watts continuous. It is extremely unlikely that the intercepted beam current would ever be high enough to require this dissipation level.

The D-Mag-195 slits utilize a cylindrical tungsten tip, radiation cooled, which is driven by a bellows stem sealed actuator shaft. Total slit width adjustment is from 0 to 1.50 inches. Vacuum leakage rate is guaranteed less than 5×10^{-9} torr-liter/second.

3.1.8 An ultra-fast closing vacuum gate valve is included between the vacuum system at the high energy tank base and the 90° analyzing magnet to protect the accelerator against shock wave damage from catastrophic vacuum failure in the beam transport system or the experimental target apparatus. In the open position, the gate valve, a D-VAC-39, has an unrestricted through aperture of 4 inches. Beam power dissipation in the closed position is 1000 watts for short periods of time.

Closure time is 30 milliseconds. Valve body and bellows are made entirely of stainless steel and the gate is an aluminum plate. All body joints are demountable-universal gold wire gasketed; permanent joints are fusion welded. The complete valve can be repeatedly baked out at temperatures up to 450° C, meeting the most stringent requirements for ultra-clean vacuum application, and is completely constructed of inorganic materials thereby being ideally suited for use in a high radiation environment.

The valve operates via a "guillotine" action of the gate. A pneumatic cylinder and electromagnet hold the gate in the open position, in opposition to the downward force of a powerful coil spring. The holding force of the electromagnet is adjusted so that it is slightly greater than that of the coiled spring. A signal from a "poor vacuum" sensing device removes power from the holding coil and the gate slams shut. Belleville washers are mounted in the valve housing to absorb the impact of closure, preventing equipment damage and excessive vibration of the gate. As the gate closes, a microswitch is activated showing the valve gate position. Vacuum conditions must be restored and the holding coil energized again before the valve can be opened. The energized coil is lowered by the operator and makes contact with the pick-up plate on the gate. Once contact is made, the gate can be raised to the open position by the air piston.

The Ultra Fast Closing Valve must be used in conjunction with a conventional vacuum valve if vacuum is to be maintained for an extended period of time. A control circuit, incorporating the Ultra Fast Closing Valve gate position microswitch, may be used to close a companion high vacuum valve. This type of valve system provides "fail safe" operation and automatic systems protection from the shock wave due to sudden vacuum failures, as well as preserving the vacuum in the protected volume.

3.2.0 90° Ion Beam Analyzing Magnet:

The custom designed single focussing Model 90-34S is supplied. This magnet is constructed with cast (.05 C) iron poles and has a mass energy product number of 60, and a radius of curvature equal to 28 inches. Consideration of field homogeniety and saturation effects, which results in an integrated field uniformity of two parts in 10^4 from low fields to fields representing a mass energy product of 52. Magnet pole edges are contoured in such a way that corner saturation will not occur at any rated flux level. A mounting pad, in a uniform field region is provided for insertion of the NMR probe.

3.2.1 The vacuum chamber, which is independent of the magnet poles, is made of stainless steel and is capable of dissipating 10 kilowatts/cm^2 continuously. Chamber lining is material whose atomic number is greater than 70. The chamber is electrically insulated and incorporates, in its metering circuitry, a beam impingement interlock. Sighting ports and telescope mounts for precision alignment of the incoming and outgoing beam tubes are provided. Vertical (height) opening inside the vacuum chamber is 1.0 inch.

3.2.2 A support base is provided for the 42-inch beam height with vertical adjustment of $\pm$ 1/2 inch and traverse horizontal adjustment of $\pm$ 1/2 inch for alignment.

3.2.3 Coils are insulated by fiber glass sleeving and vacuum impregnated with epoxy resin. Square hollow core copper conductors are used with direct water (2 gpm) flow cooling.

3.2.4 The 12 kw power supply provided with the 90° Ion Beam Analyzing Magnet is specially designed to give long trouble-free service and has many design features involving high quality refinements which are not normally apparent.

Circuit Description:

The power supply circuit consists of three closed loops. The first loop includes the power supply direct current error signal detection amplifier. This high signal-to-noise ratio amplifier can detect error signals of less than 1 microvolt, and is compatible with long leads between the controls and power supply. The second loop amplifier corrects for power line voltage variations and reduces the power supply output current ripple. The third pre-regulator circuit loop maintains a constant voltage across the regulator power transistors. The pre-regulator includes a voltage comparator circuit and a motor-driven variable transformer. This pre-regulator system is used so that sensitive measuring instruments will be free of the effects of high electrical noise levels produced by phase delay silicon (SCR) rectifier circuits.

D. C. Signal Wiring:

The effect of contact potentials in the d. c. error detection circuits has been minimized. Gold-plated plugs and receptacles, silver-plated wiring, and cadmium-tin alloy solder at all junctions are used. Interconnections are made with insulated twisted shielded wire; with a minimum number of connections. All shields are insulated and grounded at a common point to prevent circulating currents and excessive pickup.

The amplifier circuit is mounted in an electrically insulated and temperature-regulated magnetically and electrostatically shielded plug-in unit. This electrically guarded circuit gives excellent isolation and common mode rejection. Temperature regulation essentially eliminates false error signals from contact or junction potentials produced by variations in ambient or equipment temperatures.

Current Reference Resistor:

The current reference resistor is heat-stabilized Manganin. It is immersed in a temperature-regulated and continuously stirred oil bath oven, which is maintained at its optimum temperature of 50° C ($\pm$ 0.3° C) to obtain a stability of less than 5 ppm. The oil bath oven is independent of the temperature or quality of the cooling water. The high dielectric bath minimizes contamination of the voltage signal taps.

Remote Control Panel:

The remote control panel contains a load current meter, the power standby-off, and polarity reversal illuminated push-button switches. The illuminated switches indicate the function and condition of the switched circuit. In addition, the power transistor fuse fault condition is indicated.

The 10-turn, coarse and fine potentiometers, reference voltage zener diode are mounted within a shielded and temperature-regulated enclosure. The zener diode is operated by a constant voltage power supply which uses a special shielded guarded transformer to minimize a.c. capacitive coupling through the circuit.

Specifications:

Model No:	1400-301 A
Power Rating; kW:	12
Output Current; amps:	0.5-300
Output Voltage; volts:	40
Load resistance to utilize maximum power rating; ohms:	.13
Current Ripple[a]; ma: P. to P.	60
AC Input; 50/60 Hertz:	
Voltage:	480 volts, 3 Ø, 4 wire
kvA:	15
Voltage:	120 volts, 1 Ø, 2 wire
kvA:	1

(a) Maximum ripple having an inductive load time constant greater than 1 second. Field ripple in a solid iron core magnet is reduced by about 0.02 x current ripple.

Specifications, cont'd.

Weight: Power Supply; lbs.	650
Controls; lbs.	20
Water Requirements:	0.15 gpm per Kilowatt, 85° F., maximum, p = 20 psi.
Dimensions: inches, h x d x w	
Power Supply:	76 x 28 x 23
Controls:	3-1/2 x 8 x 19
Current regulation:[b]	$\pm$ 5 x 10^{-6} for 10% line voltage or load resistance change due to I^2R
Current Stability:[b]	$\pm$ 5 x 10^{-6} for 15 minutes (short term)
	$\pm$ 1 x 10^{-5} for 8 hours (long term)
Current Adjust. Resolution:[c]	Coarse 1 x 10^{-3}
	Standard Fine 1 x 10^{-4}
External Modulation:	0 to 1.1 volts, negative, for full current range.
Polarity Reversal:	Illuminated push-button switch located on the remote control panel sets and indicates polarity. An automatic polarity reversal switch is operated when the variable transformer runs down to zero volts.
Metering:	Assembly Products Stylist Model 361, 0 - 50 Millivolt d.c. with appropriate scale

(b) Between 20% to 100% of the power supply rating and measured in a magnet field with High Voltage Engineering Corporation's Nuclear Magnetic Resonance (NMR) Fluxmeter.

(c) Continuously adjustable over the entire current range with coarse and fine 10-turn potentiometers. The standard fine control is over any 10% of total current range. Fine controls adjustments over any 1% of total current range are optional.

Specifications, cont'd.

Protection:

1. Power transistor overvoltage zener diode clamp

2. Power diode across power supply output to provide current decay path for inductive loads when the power is turned off

3. The power supply has complete interlock protection with an "interlock-standby on" panel indicator light for:

   a) Phase current unbalance

   b) Cabinet doors

   c) Power transistor fuses

   d) Circuit breakers and fuses for a.c. power

   e) Auxiliary interlocks for magnets or other equipment

   f) Power transistor over current

   g) Power transistor over temperature thermostats

3.3.0 The High Voltage Engineering Corporation Nuclear Magnetic Resonance (NMR) fluxmeter provides an accurate, convenient, and reliable determination of magnetic field strength. It is supplied with two (2) probes, a digital frequency counter, interconnecting switches and all necessary cables. This NMR fluxmeter has an extremely high signal-to-noise ratio of 20 db and a resolution of two parts in 10^5. A single, proton-rich probe covers the entire range from .5 to 19 kilogauss eliminating the two limitations of other NMR fluxmeters; probe changing or shunting, and the use of less sensitive nuclear samples of lithium or deuterium. One probe is supplied for the 90^o analyzing magnet and one for the wide-angle switcher.

3.3.1 A nucleus, when placed in a magnetic field, precesses about an axis parallel to the direction of the magnetic field. The precessional rate (frequency) of the nucleus is directly proportional to the magnetic field strength. When the nuclear sample is coupled to a variable frequency oscillator, the resoluting frequency of the system may be easily determined. The magnetic field strength is thereby established by reference to the gyromagnetic ratio for the particular nucleus.

3.3.2 Probe:

The probe is ruggedly constructed to permit stable mounting for noise-free operation. The sensing center is 1/2" from the end of the probe.

3.3.3 Oscillator:

The oscillator is rigidly attached to the probe and is designed to detect small changes in the frequency of the nuclear sample. The frequency range is from 2 to 81 megacycles. Six remotely switched frequency bands correspond to magnetic field intensities of 0.5 to 19 kilogauss. Maximum sensitivity is provided in part by circuity designed to automatically maintain the oscillator amplitude at a very low level.

The axis of the field sweep coil is perpendicular to the oscillator coil. It modulates the magnetic field in the vicinity of the oscillator coil. Oscillator tuning is done from the display and control unit.

3.3.4 Display and Control Unit:

The display and control unit provides complete control and monitoring for the fluxmeter's six frequency bands.

While the magnetic field is continuously modulated at 60 cycles, two oscilloscope sweep frequencies provide location of the resonance pip. A 60 cycle sweep easily locates the pip, while the high resolution, 120 cycle sweep permits coincidence of two pips rather than the visual centering of one on the oscilloscope. The accuracy of the fluxmeter, 2 parts in 10^5, is limited by the resolution of the oscilloscope trace on the scan.

Once the resonance point has been located, the fluxmeter frequency will automatically follow changes in the magnetic field within the particular band and thereby provide a continuous indication of field strength. This automatic tracking feature operates over the entire frequency range of the instrument with a stability of ± 2 parts in 10^5, or better, for a signal to noise ratio of 20 db minimum.

An error voltage output of ± 1 volt is provided, which may be incorporated into a feedback system to maintain a constant magnetic field strength.

3.3.5 Feature Summary:

1.	Very High signal to noise ratio	20 db minimum
2.	Scope Sweep	60 Hz/120 Hz
3.	Display	3" (7.5 cm) Cathode Ray Tube
4.	Field Sweep	Variable from 1.2 to 15 gauss
5.	Power Requirements	105-125 volts, A.C., 50-60 Hz; 160 watts
6.	Error signal output	Up to 1 volt/gauss
7.	Short term stability	1 part in 10^5
8.	Long term stability	1 part in 10^4
9.	Probe Constant	4.2577 MHz/kg

3.4.0 A slit signal feedback and stabilization system is provided which senses analyzed beam positions in the median plane of the analyzer, and corrects the accelerator terminal voltage -- hence the ion beam energy -- by varying the level of a high-pressure corona discharge in the insulating gas.

Stabilization and control of the terminal voltage is done by a method similar to that described by Gere[8]. Features of the system are:

a. Primary error signals can be derived from two separate sources i.e., the current intercepted on the output slits of the analyzing magnet will provide a correction signal for low frequency changes in terminal voltage, and high frequency changes will be sensed directly by a capacitive pickoff located near the high voltage terminal.

b. Suitable electronics are provided so that terminal voltage control can be accomplished with slit currents smaller than 10^{-10}A.

c. Additional provision is made so that in the absence of an error signal on the slits, control of the accelerator terminal voltage will revert to the secondary indicator which is the generating voltmeter.. This secondary voltage indicator functions independently of the accelerated ion beam. Control of the accelerator terminal voltage shall return to the primary feedback system (described in a. above) as soon as a suitable error signal returns to the slits.

d. Provision is made (by means of manual switch selection) so that the control of the accelerator can be given over entirely to the primary control system (a. above) or to the secondary indicator, or finally, that the control of the terminal voltage is automatically shared between the primary and secondary indicators as described in the preceding paragraph.

3.5.0 Beam line components as follows are provided between the 90° Ion Beam Analyzing magnet and the wide-angle switcher:

3.5.1 Bellows, reducers, insulated unions, and stainless steel vacuum plumbing as required to interconnect all major components.

3.5.2 Beam profile scanner (See 3.1.6) located immediately upstream of the 90° ion beam analyzer's image slit position.

3.5.3 Double image slit assembly rated identically to the double object slit assembly described in section 3.1.7.

3.5.4 A high vacuum auxiliary pumping station is located between the double slit assembly and the wide angle switching magnet.

An ion pump which is rated at 250 liters/second at vacuums of 10^{-5} Torr or better is used. A 4-inch line connects the pump, via a 4-inch bellows stem sealed gate valve, directly to the beam transport tube.

3.5.5 A 4-inch bellows stem sealed, remotely operated, gate valve[a] is included to isolate the wide angle switcher from the main vacuum system.

3.5.6 A 4-inch by 2-inch reducing "Tee" is included after the gate valve, with a right angle 2-inch valve, for use as roughing port.

[a] Valve description in 3.1.1

3.6.0 Wide Angle Ion Beam Switching Magnet:

A double focussing[a] wide angle switcher is provided to direct the analyzed ion beam into various target areas. The magnet is mounted for the 42-inch standard beam centerline height and is rated as a Mass Energy product 80 at 45°. Exit ports are provided at 0° and:

Right side: 15°, 30°, 45°, 65°

Left side: 25°, 45°, 65°

Degaussing coils, capable of reducing the residual field to a value which permits steering an ion beam through the 0-degree exit port, are included. An NMR probe (See section 3.3.0) is provided and inserted into a homogeneous field volume for precision flux measurement.

3.6.1 The primary magnet coils are water-cooled, Class F insulated (155° C), low impedance, hollow core, square OFC tubing. Conductors are insulated with fiber glass sleeving, not tape. After winding, they are vacuum impregnated with high-temperature epoxy resin. All splices are fluxless silver soldered with ferrule inserts to ensure an unobstructed coolant passage. Thermal switches are mounted on each coil to protect against failure due to insufficient waterflow. Like all High Voltage Engineering magnet coils, the coils are guaranteed for seven years on a pro rata basis.

[a] -- at 45° Left and 45° Right

3.6.2. An aluminum wrap-around chamber is provided which is lined with material whose atomic number is greater than 70. An aluminum chamber is used since all optics calculations indicate a relatively large beam size, and hence a low beam power density, in the chamber. Estimated levels for full beam dissipation on the chamber during operating conditions are less than 200 watts per cm^2. Vertical opening in the chamber is 1 inch. The zero degree exit port is equipped with a provision for mounting a transport system alignment telescope. All exit ports not specified in the subsequent text of this proposal are terminated in blank off flanges.

3.6.3 The power supply furnished with the wide-angle switcher is a 12 kW unit identical to that used to power the 90° Ion Beam Analyzing magnet and described in detail in section 3.2.4. An additional feature of the power supply used with the switcher is a polarity reversal switch, which is necessary to switch from the left leg to the right leg or vice-versa.

3.7.0 Switcher Beam Leg Number 1--Left 65°

The left 65° beam leg has a beam centerline height of 42 inches, and is approximately 20 feet long, ending at target location number 1. This leg includes:

3.7.01 3-inch bellows and support assembly.

3.7.02 4-inch bellows stem sealed remotely operating gate valve.

3.7.03 Beam line support fixtures as needed before the shielding wall. All beam transport components located downstream of the shielding wall will be mounted on a cabinet-type beam line support system of welded steel modular cabinet frames. Conduit connectors bridge the space between cabinets (or leg supports) and act as intermediate beam line component supports, as well as being raceways for plumbing and wiring.

3.7.04 3-inch bellows and support assembly.

3.7.05 3-inch aperture magnetic quadrupole doublet lens as described in section 3.1.4.

3.7.06 Power supply for item 3.7.05. Described in section 3.1.5.

3.7.07 3-inch bellows and support assembly.

3.7.08 4-inch by 2-inch reducing "Tee" with a Bayard-Alpert type nude ion gauge complete with power supply and remote indicating meter at the main control console. The gauge has two replaceable filaments. In the event of one filament failing, the space can be put into service simply by removing the external keyed plug and re-inserting it with a 180° rotation. This is done without breaking the vacuum in a matter of seconds. Stainless steel and ceramic construction permit bakeout to the temperature limits of the elastomer seal. Sensitivity of the gauge is 100 microamperes per micron at 10 milliamperes of grid current.

3.7.09 High vacuum station consisting of a 100 liter/second (at vacuums of 10^{-5} Torr or better) ion pump, a 4-inch connecting line, a 4" gate valve, all necessary power supplies and mounting hardware.

3.7.10 4-inch bellows stem sealed remotely operating gate valve.

3.7.11 4-inch by 2-inch reducing "Tee" with a 2-inch opening manually operated valve and roughing connection.

3.7.12 Beam profile scanner head with remote monitor readout. See section 3.1.6 for detailed description.

3.7.13 4" Bellows and Support Assembly.

3.7.14 Insulated Faraday Cup for ion beam intensity measurement.

3.8.0 <u>Switcher Beam Leg Number 2--Right 45°</u>

The right 45° beam leg has a beam centerline height of 69 inches within 4 feet of the switcher output, due to a shift in facility floor elevation, and is approximately 36 feet long ending at target location number 2. This leg includes:

3.8.01 3-inch bellows and support assembly.

3.8.02 4-inch bellows stem sealed gate valve.

All beam transport components on this beam leg will be mounted on a cabinet-type beam line support system of welded steel. Conduit connectors shall connect the cabinet mount and leg supports. No individual length of 4" stainless steel drift tube shall exceed 8 feet in length. Standard 4" x 2" reducing tees shall be used to connect the 8 foot (or shorter) sections of drift tube where necessary.

3.8.03 3-inch bellows and support assembly.

3.8.04 Magnetic quadrupole doublet lens (same as item 3.1.4). This lens shall be operated from the same power supply which services item 3.7.05. A simple switching panel shall be provided at the control console so that the power supply may be switched from item 3.7.05 to item 3.8.04 quickly and conveniently.

3.8.05 Bellows and support assembly.

3.8.06 Long drift tube interrupted every 8' with reducing tees as described earlier.

3.8.07 4-inch by 2-inch reducing "Tee" with a Bayard-Alpert type nude ion gauge complete with power supply and remote indicating meter at the main control console. The gauge has two replaceable filaments. In the event of one filament failing, the space can be put into service simply by removing the external keyed plug and re-inserting it with a 180° rotation. This is done without breaking vacuum in a matter of seconds. Stainless steel and ceramic construction permit bakeout to the temperature limits of the elastomer seal. Sensitivity of the gauge is 100 microamperes per micron at 10 milliamperes of grid current.

3.8.08 Magnetic quadrupole doublet lens (same as item 3.1.4).

3.8.09 Power supply for item 3.8.08. Described in section 3.1.5.

3.8.10 High vacuum station consisting of a 100 liter-second (at vacuums of 10^{-5} Torr or better) ion pump, a 4-inch connecting line, a 4" gate valve, all necessary power supplies and mounting hardware.

3.8.11 4-inch bellows stem sealed remotely operating gate valve.

3.8.12 4-inch by 2-inch reducing "Tee" with a 2-inch opening manually operated valve and roughing connections.

3.8.13 Beam profile scanner head with remote monitor readout. See section 3.1.6 for detailed description.

3.8.14 4-inch bellows and support assembly.

3.8.15 Insulated Faraday cup for ion beam intensity measurement.

4.0.0 Recirculating Cooling Water System:

A closed circuit recirculating cooling water system is provided to maintain correct operating temperatures in the magnet coils, diffusion pumps, ion source heat exchanger, and other accelerator or beam transport components which might be severely damaged by accumulation of deposits from the city water. The cooling system is designed for the most economical consumption of "raw" city water.

4.1.0 Equipment Description:

The water system will be a closed double loop arrangement consisting of one chilled (50°F) water loop and one warmer (70 to 85°F) loop. The chilled loop will have two separate circulating pumps; one for the vacuum systems and one for accelerator tank cooling coils. Warmer water will be circulated through a demineralizer by a separate pump and will be used to cool the analyzing magnet, switcher magnet, and other beam line components. Both loops are part of a 15 ton chiller system with a 150 gallon storage tank.

City water requirements (raw water) for the chiller are:

at 85°F - 45 GPM

at 88°F - 65 GPM

4.2.0 Warm Water Supplied by System:

The amount of 85°F water required by various accelerator system components is:

Inflection Magnet =	1 GPM
Inflection Magnet Power Supply =	1 GPM
Tank Roughing Pump =	1/4 GPM
High Energy Extension Quadrupole =	3/4 GPM
Analyzing Magnet =	2.5 GPM
Analyzing Magnet Power Supply =	2.5 GPM
Switcher =	2.5 GPM
Switcher Magnet Power Supply =	2.5 GPM
Switcher Extension (Quadrupoles) =	2.25 GPM
Post Acceleration Ion Beam Chopper =	1.5 GPM
	16.75 GPM

4.3.0 Chilled Water Supplied by System:

The amount of 50°F water required by various accelerator system components is:

Gas Transfer System =	6 GPM
Accelerator Tank Cooling =	7.3 GPM
Accelerator Vacuum System =	1 GPM
Injector (Source & Pump)	5 GPM
	19.3 GPM

5.0.0 Optional Equipment:

Optional equipment is available at additional cost as outlined in Section 10.0.0, Financial Considerations. Descriptions are included in this section of the specific optional items requested by the University.

5.1.0 Negative Helium Ion Injector:

The negative helium ion injector proposed is complete and is designed to be mounted on the empty 30° port of the diode source injector inflection magnet.

The hardware consists of a duoplasmatron type ion source for the production of positively charged helium ions, an alkali metal vapor charge attachment cell for the formation of negative ions, and all necessary pumps, power supplies and controls.

Basic principle of operation is the near resonance exchange that takes place in alkali metal vapor. Either lithium or potassium may be used as the attachment vapor although lithium is preferred because resonance occurs at a high energy and the ion beam is more suitably matched to the accelerator.

5.1.1 The duoplasmatron ion source is a compact Von Ardene type device which provides controlled plasma densities and variable ion beam focusing. The source head includes a tungsten hairpin filament, an electromagnet for controlling the discharge plasma density, an intermediate electrode, and an aperture plate. The magnetically confined plasma penetrates a small aperture in the plate and enters an expansion cone forming a large boundary surface of low density plasma. This expanded plasma configuration gives better voltage holding characteristics and improved beam focusing at normal extraction potentials. The source is mounted on the alkali metal vapor cell pumping box.

5.1.2 An adjustable optical bench supports and aligns the individual elements of the extraction, focus, and exchange electrodes inside the pumping box. Each element has its own high voltage vacuum feed-through bushing for the connection of cooling liquid, electrical, and gas lines. The power supplies for the three elements are independently controlable; consequently, the beam focus and negative ion yield may be optimized for each ion species or attachment vapor used. Support insulators are well shielded against contamination for reliable operation. The lithium exchange cell, vapor feed reservoir and condensing baffles are easily removed for cleaning and re-charging. A gas canal can readily be substituted for the lithium target if desired.

Typical data which has been obtained on an EN Tandem Accelerator is as follows:

Exchange Vapor or gas	Particle and current (μA)(1)	Beam injection energy (keV)	Analyzed current (μA)
H_2	1H - (50)	60	
H_2	3He - (1.25)	120	.70 $^3He^{++}$
H_2	4He - (.75)	120	.45 $^4He^{++}$
K	3He - (5.0)	38.5	1.7 $^3He^{++}$
K	4He - (7.0)	39.2	2.6 $^4He^{++}$
Li	3, 4He - (5-7)	~60	3.5 $^{3,4}He^{++}$

5.1.3 Vacuum system included in the mount for the pumping box consists of a 6 inch NRC oil diffusion pump with a cold cap, a 6" air actuated gate valve, and a 10 cubic feet/minute forepump. All necessary vacuum measurement and interlocking devices are included.

5.1.4 Local controls are provided, in a cabinet adjacent to the helium negative ion injector mount, and include extraction and focus power supplies as well as a vacuum control panel. Operational controls are located at the main accelerator control console.

Power required by the negative helium ion injector is 9.5 KVA of 3 phase 120/208. Water required is 5 GPM at 80°F supplied at a maximum inlet pressure of 60-90 PSI. Adequate capacity has been provided with the closed circuit water system (see Section 4.0.0) to handle this flow. Compressed air is required at 90-100 PSI.

5.1.5 Helium Ion Injector Performance:

Performance specifications of the accelerator system when equipped with the Helium Ion Injector described in this section will be:

He^4 ion energy out of the accelerator:

3 to 12 MeV continuously variable

He^4 ion current: (measured Faraday currents)	2 μA at 12 MeV 2 μA at 7.5 MeV 2 μA at 3 MeV

All He^4 ion currents shall be demonstrated at the target location on beam leg number 2. Ninety (90) per cent of the specified current shall be contained in a target spot 5mm x 5 mm in area.

5.2.0 Additional Beam Leg:

This beam leg contains all components listed for the Left 65° leg described in section 3.7.0 with the exception of items 3.7.06, 3.7.09, and 3.7.12.

5.3.0 Post Acceleration Ion Beam Chopping:

The post acceleration chopping system will include a Chopper Driver, a Final Amplifier, and a Post Acceleration Chopper as shown in Figure I.

The chopper driver will receive its input signal from the basic sweep frequency of the Pre Acceleration Pulsing System which is described in Section 1.5.0. This unit, which includes phasing and amplitude controls, will drive the final amplifier.

Signal from the final amplifier applied to the deflection plates of the post acceleration chopper will sweep the pre-acceleration pulsed beam across the chopper aperture plate.

A 100 liter/second ion pump will be provided following the post acceleration chopper to pump out the outgassing products produced by the impingement of beam on the chopping aperture.

All materials in the beam line near the chopper which are not directly shielded will be covered with a material of atomic number greater than 70.

Pulse width (FWHM) on the target after the chopper will be less than 1.0 nanosecond for 8.0 MeV protons and 12.0 MeV He^4 ions. Spot size at Target Number 2 will be 3 millimeters x 3 millimeters.

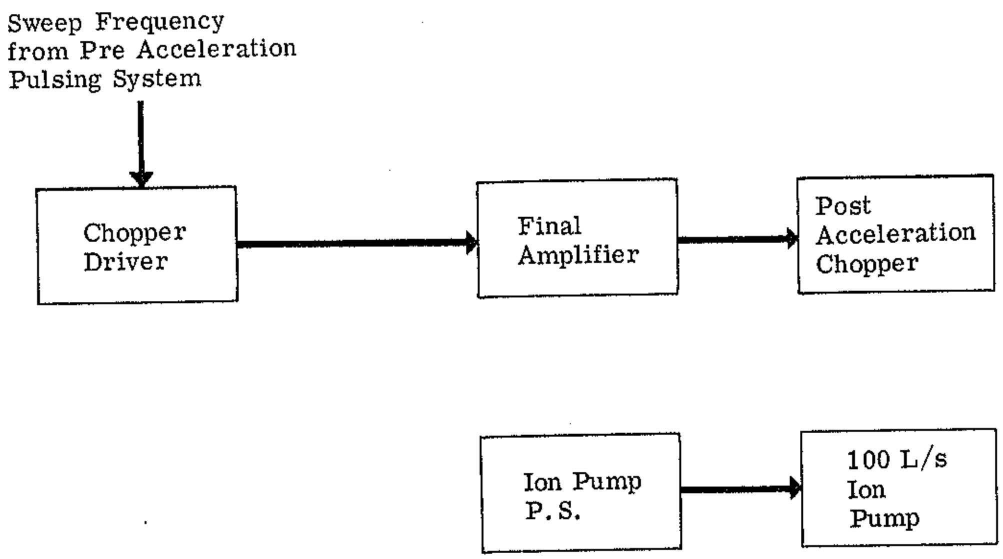


Figure 1 - Post Acceleration Chopping System

SECTION 1.5.0

5.3.1 Post Acceleration Chopper System Calculations:

The following calculations are made to demonstrate that the system provided will perform the necessary beam chopping.

The following derived equation is used to calculate the necessary voltage per nanosecond $\left(\frac{dv}{dt} \right)$ that the chopper must be capable of delivering.

$$V_{rms} = \sqrt{W\,Q\,X_c} = \sqrt{\frac{W\,Q}{2\pi f C}}$$

$$V_{pk} = \sqrt{2}\; V_{rms} = \sqrt{\frac{W\,Q}{\pi f C}}$$

$$\frac{dv}{dt} = V_{pk} \sin 2\pi f$$

where $dt \ll \frac{1}{f}$

then

$$\frac{dv}{dt} = V_{pk}\, 2\pi f = 2\sqrt{\frac{W\,Q\,\pi f}{C}}$$

where:

W	=	RF Power Available
Q	=	Chopper Tank Circuit Q
C	=	Output Circuit Capacitance
f	=	Chopper Frequency
V_{pk}	=	Peak Deflection Voltage

Using the following values for the above:

$W = 2.5$ kw max. at an efficiency of 62.5 % [a]

$Q = 10^3$

$C = 10$ pf

$f = 20$ Mc

Then

$$\frac{dv}{dt} = 2\sqrt{\frac{2.5 \times 10^3 \times 2 \times 10^7 \times \pi}{10^{-11}}}$$

$$\frac{dv}{dt} = 2\sqrt{5\pi} \times 10^{12}$$

$$\frac{dv}{dt} = 7.92 \times 10^3 \frac{v}{ns}$$

Therefore the system is capable of providing 7.92 kV/ns for the deflecting the beam.

To calculate the dv/dt required at different energies, the following relationship was used:

$$\frac{dv}{dt} = \frac{2\, d\, D\, V_\circ}{\ell\, L}$$

---

a Based on prior design experience.

where

d	=	Diameter of aperture
D	=	Distance between the deflection plates
V_o	=	Energy of the beam
ℓ	=	Length of the deflection plates
L	=	Distance between the center of the deflection plates and the chopping aperture.

The following values, from the beam optics at 5 MeV, are used:

d	=	0.2 inches
D	=	1.5 inches
L	=	120 inches
ℓ	=	12 inches

Then

$$\frac{dv}{dt} = \frac{2 \times 2 \times 10^{-1} \times 1.5 \quad V_o}{12 \times 120}$$

$$\frac{dv}{dt} = \frac{10^{-2}}{24} \quad V_o$$

At $\quad V_o = 2$ MeV

$$\frac{dv}{dt} = \frac{2 \times 10^{4}}{24} = 0.825 \quad \text{kV/ns.}$$

At $V_o = 5$ MeV

$$\frac{dv}{dt} = \frac{5}{24} \times 10^4 = 2.08 \text{ kV/ns} .$$

At $V_o = 11$ MeV

$$\frac{dv}{dt} = \frac{11 \times 10^4}{24} = 4.59 \text{ kV/ns}.$$

This shows the required voltage per nanosecond over the energy range; clearly less than the system capability.

Using the relationship of

$$\frac{dv}{dt} = V_{pk} \sin 2 \pi f$$

for small angles becomes:

$$\frac{dv}{dt} = 2 \pi f V_{pk} .$$

CHECK

The V_{pk} was measured on a previous machine as being plus 40 kV at 20 Mc and was limited by a plate spacing of 1 cm and not by the power capability of the chopper:

$$\frac{dv}{dt} = 2 \pi \times 2 \times 10^7 \times 4 \times 10^4$$

$$\frac{dv}{dt} = 5.02 \text{ kV/ns} .$$

This demonstrates again that the described system can provide the necessary drive for beam chopping.

6.0.0 General Performance Specification:

The following sections outline the performance specifications of the primary sub-systems which comprise this accelerator system:

6.1.0 Accelerator Terminal Voltage is continuously variable from 0.8 to 5.5 million volts:

Terminal Voltage Stability

Long Term:	± 10 kV without analyzing magnet
	± 1 kV when used with an analyzing magnet
Short Term:	± 10 kV without analyzing magnet
	± 1 kV when used with an analyzing magnet

6.2.0 D.C. Positive Ion Current =

Energy MeV	Current, Microamperes Protons	Deuterons
11.0	25	25
8.0	100	75
5.0	100	75
2.0	50	35

All D.C. currents will be measured at the target on beam leg number 2 located as described in section 3.8.0. Ninety (90) per cent of the specificed beam current will be contained in a target spot 3 mm x 3 mm.

6.3.0 Pulsed Positive Ion Current (with klystron bunching)

Pulse shape:	gaussian (approx.)
Pulse Width[a]: (FWHM)	less than, or equal to 1.0 nanosecond for protons; 1.5 nanoseconds for deuterons.
Peak Pulse Current[b]:	greater than 2000 micro-amperes for 5 MeV and 11 MeV for protons.
	1000 microamperes for 5 MeV and 11 MeV deuterons
Repetition Rate:	5.0 MHz
Countdown Factors:	1/2, 1/4, 1/8, 1/16, 1/32

All pulsed currents will be measured at the target location on beam leg number 2 located as described in section 3.8.0. Ninety (90) per cent of the specificed current will be contained in a target spot 3 mm x 3 mm.

6.4.0 High Energy Beam Quality:

The beam emittance for the full rated proton beam at 5 MeV will be less than or equal to 1.4 cm-mrad for the D-C mode and less than or equal to 4.6 cm-mrad for the pulsed mode.

a - measured using time-of-flight measurement technique.

b - determined from average current, repetition rate, and pulse width as measured above according to equation $I_{ave} = I_p W N$ where W is pulse width (FWHM) and N is repetition rate.

7.0.0 Performance Demonstrations and Acceptance Tests:

In-Plant Tests: The Ohio University faculty may participate in and witness any in-plant tests that are performed at High Voltage Engineering Corporation's Burlington factory. The Buyer will be notified at least two weeks in advance prior to tests of major significance.

Acceptance Tests: All tests on which the final acceptance of the acceleration system is based will be made at the Ohio University facility. Such testing will not begin until both the representatives of Ohio University and High Voltage Engineering Corporation feel that it is safe to conduct such tests. The following will constitute the acceptance tests:

7.1.0 Vacuum Tests: All vacuum lines associated with the injector system, accelerator system, and beam transport system will be evacuated with the system vacuum pumps. A check for leaks will be conducted using a mass-spectrometer leak detector (provided by Ohio University), and the rated static vacuum of 1×10^{-6} Torr will be demonstrated. All pressure and vacuum lines associated with the insulating gas storage and handling system will also be demonstrated to be free from leaks.

7.2.0 Magnet Performance Tests:

Magnetic field strength in the 90° Ion Beam Analyzer and the wide angle switcher will be measured at the highest and near lowest rated fields with the Nuclear Magnetic Resonance fluxmeter described in section 3.3.0.

7.3.0 Accelerator Tests:

Accelerator tests will be performed as follows:

7.3.1 Terminal voltage will be demonstrated between 0.8 and 5.5 MV as indicated and controlled by the signal from the generating voltmeter. The calibration of this device shall be checked at two energy points by means of known nuclear reaction thresholds at target #2. The stability of the GVM will be demonstrated by observing the GVM output with a differential voltmeter for 1/2 hour while operating the accelerator slit stabilized by the analyzed beam at 8 MeV. The stability of the generator operating unanalyzed using the secondary reference will then be demonstrated for 1/2 hour at the same voltage now using the differential voltmeter as the voltage measurement. For 95% of this period the voltage of the accelerator as measured by the GVM and differential voltmeter will not deviate by more than ± 10 kV. Equipment for specifically nuclear measurements will be provided by Ohio University.

7.3.2 Determination of Energy Stability of the Proton Beam:

Energy stability of the proton beam at target #2 shall be demonstrated in the D.C. mode to be not greater than ± 2 keV by the use of a nuclear reaction observed with suitable equipment supplied by the Buyer. Measurements of stability shall be performed using a resonance described above in "Determination of Energy Spread", and/or the steep portions of the threshold yield curves selected from one of the following reactions:

Reaction		Threshold Energy (MeV)
Li^7	(p, n)	1.881
C^{13}	(p, n)	3.236
F^{19}	(p, n)	4.234
Al^{27}	(p, n)	5.797
S^{34}	(p, n)	6.451
Ni^{60}	(p, n)	7.023

Stability measurements will be made at two (2) energies as determined by the Buyer. Stability measurements at a given energy will consist in repeated observations over a period of two hours of the yield from a reaction with the incident energy set at a value corresponding to a position half-way up the step in the case of a thick-target resonance, and a position on the steep portion of the rise above threshold for the case of above (p, n) reactions.

The repeated observations at a given half-way point will each extend for a sufficient time to accumulate approximately 1% statistics on the counts before beginning a repeat run. This will repeat over and over until two hours are completed. The variations in counting rate from one repeat run to another will not exceed an amount that would place the energy outside an interval of ± 2 keV, according to a previously determined yield curve. The stability measurements will be performed at full rated proton currents given above, or at such lesser beam currents as the Buyer deems suitable for the particular target configuration for the resonance or threshold under consideration.

7.3.3. Energy Calibration of Control System:

The energy calibration of the control system as a whole shall be determined by the measurement of the NMR reading for six (6) energies using known resonances and/or threshold reactions[b] such as those given in the previous section on Energy Stability within the range between 1.6 MeV and 8.0 MeV. The target for these measurements shall be at target #2 location, as above. During this test, the slits of the analyzing magnet may be adjusted and accuracy required for this test, except that in no case shall the beam current on target #2 be less than 10 μA unless specified by the Buyer at the time of the test. The calibration constant of the analyzing magnet and control system shall be determined at one energy where the threshold or resonance energy is known according to a standard reference work, such as that of Marion[9], to better than 1.0 keV. The proton kinetic energy, E, will be taken then to be given by

$$E\left(1 + \frac{E}{2M_oC^2}\right) = K\, f^2\; g^2/M_o$$

where E = proton kinetic energy in MeV

f = frequency of the nuclear magnet resonance fluxmeter in MHz

g = effective charge of the ion traversing the magnetic field

M_o= rest mass

c = velocity of light

k = calibration constant of the magnet

For protons, this expression reduces to

$$kf^2 = 1.0073\ E\ \ 1 + \left[\frac{E}{1876.5}\right]$$

where M_o for the proton is taken to be 1.007277 u and 1 u = 931.480 MeV (^{12}C mass system).

Threshold or resonance energies will be measured for the other five energies. The interpretation of the location of these energies from the data shall be consistent with that given by Marion.

These measured energies of calibration shall be equal to those given by Marion within ± 0.1% of the threshold or resonance energy being considered.

7.3.4 Steady state positive ion beam currents shall be demonstrated using a Faraday cup provided by the High Voltage Engineering Corporation and located at target position #2. Adequate provision will be made to suppress secondary electron emission from the target.

During these tests the following measurements will be made from time to time.

a) Beam current ripple will be measured with an oscilloscope provided by the Buyer.

b) Beam size will be measured with an aperture defined by movable slits located within 0.5 meter from the Faraday Cup positioned at target #2. Ninety (90) per cent of the guaranteed maximum current will be transmitted through a 3 mm x 3 mm aperture. The slit assembly will be furnished for the duration of the tests by the seller. By agreement between the Buyer and Seller, beam measurements may be made with a beam profile monitor.

D.C. beam current acceptance will be for 4 hours, with occasional manual adjustment and will be conducted as follows:

Energy	Particle	D. C. Current	Time
11.0 MeV	P	25 microamperes	1/2 hr.
8.0 MeV	P	100 "	2 "
8.0 MeV	P	5 "	1/2 "
5.0 MeV	P	100 "	1/2 "
2.0 MeV	P	50 "	1/2 "
		Total	4 hours

7.3.5 Nanosecond Pulsing and Bunching:

Measurement shall be made of the duration and average current in the chopped but unbunched proton beam. After bunching, acceptance of the pulsing and bunching system performance for both protons and deuterons shall be based on average current measured in a suitably-biased Faraday cage and time spread of the prompt gamma rays from the target measured by time-of-flight techniques. This time spread measurement will be made using suitable gamma detection and time measurement equipment furnished by the Buyer. Proper functioning of the countdown circuit shall be demonstrated on all ranges. Peak pulse amplitude will be determined in accordance with the equation: $I_{ave} = I_p W N$ where I_{ave} is average current, I_p is peak pulse amplitude, W is full pulse width at 1/2 peak amplitude as measured above, and N is repetition rate.

To aid in proper adjustment of the pulser controls a pulse monitoring system will be used. This will consist of a special coaxial target provided for the duration of the test by the seller and a Tektronix Model 661 oscilloscope with Model 4S2 plug in unit provided by the Buyer.

Pulsed beam current acceptance runs will be for 3 hours, with occasional manual adjustment, and will be conducted as follows:

Energy	Particle	Pulsed Beam Current	Time
11.0 MeV	P	I_p = 2000 microamperes	1/2 hr
8.0 MeV	P	I_p = 2000 "	2 "
5.0 MeV	P	I_p = 2000 "	1/2 "
		Total	3 hours

8.0.0 Optional Additional Demonstrations and Tests: Deleted

Extensive and time-consuming additional demonstration tests are available on an optional fee basis as described in section 10.

8.1.0 Beam Emittance Measurement: Deleted

For each of the two modes of operation, DC and pulsed, at an energy of 5 MeV, the Seller will make an emittance demonstration in which the beam is focused to a minimum size (waist) at a set of slits somewhere downstream of the machine's high-energy quadrupole. The beam size will be measured with these slits. A second set of slits spaced axially either downstream or upstream from the first set will be used to measure the increase in beam size. The product of the small size times the difference between the beam sizes divided by the distance between the pairs of slits will be equal to or less than the guaranteed emittance figure.

A Faraday cage for beam intensity measurement will be located downstream of both slit assemblies.

The procedure for demonstrating beam emittance for each mode of operation will be as follows:

With both slit assemblies wide open, the accelerator will be set up to deliver rated beam into the Faraday cage. One slit assembly will be closed in both planes to dimensions predetermined by calculations to be close to actual focused spot dimensions obtainable at that position. The high energy quadrupole and steerers will then be used to peak the beam transmitted through this slit assembly. A few readjustments of the slit dimension, lens, and steerers may be necessary to insure that the beam is actually being focused to minimum dimensions (waist) at this slit assembly. Having achieved this condition, the slits will be opened wide in both planes; then the slit in the horizontal plane closed down to reduce the current transmitted to the Faraday cage by 5% taking care to clip the beam approximately equally on each side. This slit opening will be taken to be the full focused beam width, X_1. The other slit assembly will then be closed down in the horizontal plane to reduce the current transmitted to the Faraday cage by a further 5% again taking care to clip the beam equally on each side. This slit opening will be taken to be the full expanded beam width, X_2. The emittance in the horizontal is defined as $X_1 \left(\frac{X_2 - X_1}{d}\right)$ where d is the axial separation between the slit assemblies and $\frac{X_2 - X_1}{d}$ is therefore the full angle of divergence of the beam envelope in the horizontal.

Both slit assemblies will then be opened and the procedure repeated for the vertical plane to obtain Y_1 and Y_2. The emittance in the vertical is correspondingly defined as $\frac{Y_1 (Y_2 - Y_1)}{d}$.

As an alternate, at the option of the Buyer, the emittance measurements may be made in a similar manner using 2 sets of suitably calibrated beam profile monitors or a combination of slits and profile monitors in place of the adjustable slit assemblies. In this case X_1, X_2, Y_1, and Y_2 will for the profile monitors be defined as the full width at 10% of peak amplitude of the corresponding monitor display.

8.2.0 <u>Determination of Energy Spread:</u>

The energy spread of the proton beam at target #2 shall be demonstrated in the D.C. mode to be not greater than 4 keV (FWHM) by the use of the nuclear reaction observed with suitable equipment supplied by the Buyer. Measurements of the beam energy spread, Δ, shall be performed at two (2) energies between 1.6 and 8.0 MeV by observing the measured widths, Γ_m , (i.e. FWHM) of resonances of widths, Γ , known to be not greater than 4 keV. Then Δ shall be determined from $\Gamma_m^2 = \Delta^2 + \Gamma^2$, and shall not exceed 4 keV. When thick targets are used, Γ_m shall be defined as the energy difference between the points 1/4 and 3/4 the way up the step indicating the resonance in the yield curve.

The Buyer shall determine the resonance to be used in this test and whether the target will be thick or thin. The energy-spread measurements shall be performed at the full rated proton current as given in Section 6.2.0, or such lesser beam current as the Buyer deems suitable for the particular target configuration available for the resonance under consideration.

Section 8.3.0

Schedule I Tandem Pulsed Protons

All Tests described in this schedule are to be performed in one continuous 24-hour period.

E	Particle	Peak Pulse Current, Ip.	Description	Time
11.0 MeV	P	$I_p \geq$ 2,000 μA	Freq. 5.0 MHz Bunched beam duration ≤ 1.0 nsec FWHM 90% of beam current on target #2 in 3mm x 3mm spot	1/2 hr
8.0 MeV	P	$I_p \geq$ 2,000 μA	Freq. 5.0 MHz Bunched beam duration ≤ 1.0 nsec FWHM 90% of beam current on target #2 in 3mm x 3mm spot	10 hrs.
8.0 MeV	P	$I_p \geq$ 2,000 μA	Bunched beam duration ≤ 1.0 nsec FWHM Demonstrate "Count-down" operation at 1/2, 1/4, 1/8, 1/16. 1/32 rate 90% of beam current on target #2 in 3 mm x 3mm spot	2 hrs.

Schedule I -- Continued

E	Particle	Peak Pulse Current, Ip.	Description	Time
5.0 MeV	P	$I_p \geq 2,000\ \mu A$	Freq. 5.0 MHz Bunched beam duration ≤1.0 nsec FWHM 90% of beam current on target #2 in 3mm x 3mm spot	4 hrs.
5.0 MeV	P	$I_p \geq 2,000\ \mu A$	Bunched beam duration ≤ 1.0 nsec FWHM demonstrate "Count-down" operation at 1/2, 1/4, 1/8, 1/16, 1/32 rate 90% of beam current on target #2 in 3 mm x 3mm spot	1 hr.

61/2 hours during this 24 hour period to be used for adjustment, tuning, repair, etc. by the Seller as needed. All tests are performed at target #2. — 17 1/2 hrs.

Section 8.3.0

Schedule II Tandem D. C. Protons

All Tests described in this schedule are to be performed in one continuous 25 hour period.

E	Particle	Target Number	Current D. C.	Description	Time
11.0 MeV	P	#2	25 μA	90% of beam current on target in 3mm x 3mm spot	1/2 hr.
8.0 MeV	P	#2	100 μA	90% of beam current on target in 3mm x 3mm spot	8 hrs.
8.0 MeV	P	#2	50 μA	90% of beam current on target in 3mm x 3mm spot	2 hrs.
8.0 MeV	P	#2	5 μA	90% of beam current on target in 3mm x 3mm spot	1/2 hr.
5.0 MeV	P	#2	100 μA	90% of beam current on target in 3mm x 3mm spot	4 hrs.
5.0 MeV	P	#2	50 μA	90% of beam current on target in 3mm x 3mm spot	2 hrs.

Schedule II - Continued

deleted

E	Particle	Target Number	Current D.C.	Description	Time
5.0 MeV	P	#2	5 μA	90% of beam current on target in 3mm x 3mm spot	1/2 hr.
2.0 MeV	P	#2	50 μA	90% of beam current on target in 3mm x 3mm spot	2 hrs.
2.0 MeV	P	#2	25 μA	90% of beam current on target in 3mm x 3mm spot	1 hr.
8.0 MeV	P	#1	100μA	90% of beam current on target in 3mm x 3mm spot	1/6 hr.
8.0 MeV	P	#1	10 μA	90% of beam current on target in 3mm x 3mm spot	1/6 hr.
2.0 MeV	P	#1	10 μA	90% of beam current on target in 3mm x 3mm spot	1/6 hr.
					21 hrs.

4 hours of this 25 hour period to be used for adjustment and repairs.

Section 8.3.0 (Deleted)

Schedule III Tandem Deuteron Pulsed Beams

All tests described in this schedule are to be performed in one continuous 6 hour period.

E	Particle	Peak Pulse Current, I_p	Description	Time
11.0 MeV	D	$I_p \geq 1$ ma	Freq. 5.0 MHz Bunched beam duration ≤ 1.5 nsec FWHM 90% of beam current on target #2 in 3mm x 3mm spot	1/2 hr.
8.0 MeV	D	$I_p \geq 1$ ma	Freq. 5.0 MHz Bunched beam duration ≤ 1.5 nsec FWHM 90% of beam current on target #2 in 3mm x 3mm spot	2 hrs.
8.0 MeV	D	$I_p \geq 1$ ma	Demonstrate "count-down" operation at 1/2, 1/4, 1/8, 1/16, 1/32 rate at target #2	1/2 hr.
5.0 MeV	D	$I_p \geq 1$ ma	Freq. 5.0 MHz Bunched beam duration ≤ 1.5 nsec FWHM 90% of beam current on target #2 in 3mm x 3mm spot	1/2 hr.
				3 1/2 hrs.

Remaining 2 1/2 hours to be used for adjustments and repairs.
All tests are performed at Target #2.

Section 8.3.0

Deleted

Schedule IV. Tandem D. C. Deuteron Beams

All tests described in this schedule are to be performed in one continuous 6 hour period.

E	Particle	Target Number	Current	Description	Time
11.0 MeV	D	#2	25 μA	90% of beam current on Target 3mm x 3mm spot	1/2 hr.
8.0 MeV	D	#2	75 μA	90% of beam current on target 3 mm x 3 mm spot	1/2 hr.
8.0 MeV	D	#2	35 μA	90% of beam current on target 3 mm x 3 mm spot	1 hr.
5.0 MeV	D	#2	75 μA	90% of beam current on target 3 mm x 3 mm spot	1/2 hr.
5.0 MeV	D	#2	35 μA	90% of beam current on target 3mm x 3mm spot	1/2 hr.
2.0 MeV	D	#2	35 μA	90% of beam current on target 3mm x 3mm spot	1/2 hr.

Schedule IV. Continued Deleted

E	Particle	Target Number	Current	Description	Time
8.0 MeV	D	#1	75 μA	90% of beam current on target 3mm x 3mm spot	1/6 hr.
8.0 MeV	D	#1	10 μA	90% of beam current on target 3mm x 3mm spot	1/6 hr.
2.0 MeV	D	#1	10 μA	90% of beam current on target 3mm x 3mm spot	1/6 hr.
					4 hrs.

Remaining 2 hours to be used for adjustments and repair.

Add 8.4.0 - Post acc. chopper test
4 usec pulse without
2 usec " with

9.0.0 Installation

Minor modifications to the existing building at Ohio University, which may be needed to accommodate the accelerator and the accessories described herein will be provided for by High Voltage Engineering Corporation as part of the cost of installation. The accelerator system will be completely installed, ready to begin performance and acceptance tests no later than 24 months after the date on which a contract is signed.

9.1.0 It is understood, and is considered part of any contractual obligation, that the Buyer will make available to the Seller:

9.1.1 The full time services of one electronics technician and one maintenance technician over a time period not to exceed six months.

9.1.2 The services of electricians and plumbers up to a total of 2300 man-hours subject to the restrictions that a) not more than 2 electricians and 2 plumbers may be used at any one time, and b) that no more than 160 man-hours of these tradesmen will normally be available in any one week.

9.1.3 It is expected that the part-time services of at least four graduate students will be available to assist the responsible supervisory engineer.

9.2.0 The Seller will furnish all additional personnel such as riggers, pipe fitters, welders, technicians, supervisory personnel, etc., as may be required to carry out the installation. The Seller will specifically assume responsibility for whatever modifications may be needed at the Buyer's site so that the beam centerline in the vicinity of the ion source, accelerator, analyzing and switching magnet shall be 42" above existing floor levels. The Seller will, as part of the installation, take whatever steps are deemed necessary to install the gas storage piping and pumping system at a location which is acceptable to the Buyer.

9.3.0 The Seller will supply all fork lifts or other special installation tools, except as agreed upon in the final installation contract.

10.0.0 Financial Considerations:

Terms: All prices quoted are f.o.b., Ohio University Accelerator Laboratory, Athens, Ohio.

Item	Section Number	Description	Price
1	1.0.0	Negative Ion Injector	
2	2.0.0	Tandem Van de Graaff Accelerator System	
3	3.0.0	Post Acceleration Ion Beam Transport System	
4	4.0.0	Recirculating Cooling Water System	
5	5.0.0	Optional Equipment	
	5.1.0	Negative Helium Ion Injector	
	5.2.0	Additional Switches Beam Leg Components	
	5.3.0	Post Acceleration Chopping	
		Total	
6	8.0.0	Optional Additional Demonstration and Tests	
7	9.0.0	Installation	
		TOTAL	

11.0.0 High Voltage Engineering Corporation----
Experience and Background Data:

High Voltage Engineering Corporation was founded in 1946 to develop and manufacture Van de Graaff particle accelerators. Today, the company is recognized throughout the world as the leading private producer of particle accelerators and associated equipment for nuclear physics research.

The research, development, and manufacturing facilities of High Voltage Engineering Corporation are located in modern, functional buildings encompassing more than 230,000 square feet of floor space at Burlington, Massachusetts, U.S.A. High Voltage is the leader in Tandem accelerator technology with over 17 Tandem machines installed and operating in North America as well as 14 Tandem machines in Europe.

The technical staff of the company has extensive experience in the technology required to design and build Tandem accelerators and undoubtably represents the largest single team of individuals with this particular capability.

In addition to our engineering department staff, the services of our Tandem Research laboratory group and the staff of our subsidiary, Ion Physics Corporation; are available and are frequently utilized in unified design efforts. Brief Resumes for some of the individuals available to assist in the design details of the Ohio University High Energy - High Intensity Accelerator Facility are included in the Appendix. Examination of their qualifications will clearly illustrate the remarkable and useful cross section of talent represented.

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BIBLIOGRAPHY

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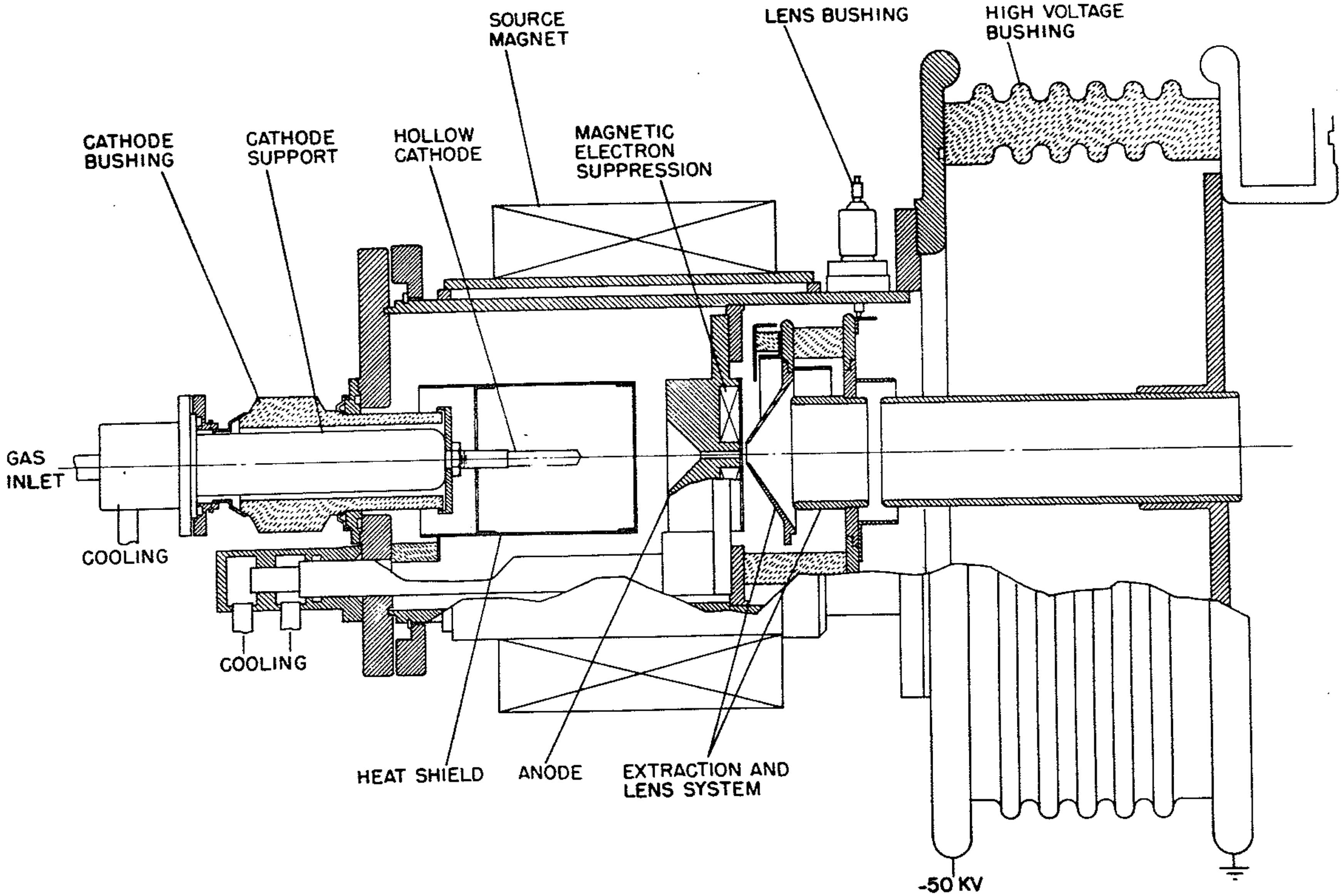
A P P E N D I X



NEGATIVE ION DIODE SOURCE

Appendix I

Appendix II

I. Estimated Operating Expense

Utilities for normal operation:

Water

Maximum city water required for chiller is: 45 GPM

Water for the accelerator tank and vacuum systems is supplied by a chilled closed loop system.

Power

120/208 volt, 3 phase 50 kVA

440 volt, 3 phase:

102 kVA is a maximum demand load for the accelerator and source equipment.

Normal running load is 50 kVA

II. Replacement Components

Foils

Foils used in the stripper are carbon foils 1/2" in diameter, and 10 μgram/cm^2 thick.

Foil life in excess of 20 hours has been observed, with beam of 100 μA of protons injected into a tandem accelerator.

Cost of carbon foils:

Box of 25 3" long, 1" wide foils mounted on glass slides, which is enough for 64 foils, including normal spoilage, costs:	$ 25.00

Charging Belt

Replacement cost of a charging belt is:	$ 555.00

Acceleration Tube:

Replacement cost of an accelerator tube with stainless steel electrodes is	$30,000.00

Diode Source Cathodes

Replacement cost for a single cathode is:	$ 70.00
Cost each, in lots of twenty four	$ 30.00

III. Estimated Normal Annual Accelerator Operating Expense

Estimated expense does not include possible unpredictable component failures, but includes normal recurring expenditures which may be objectively predicted. Accelerator tube life and belt life are minimum figures for normal operation. 5000 hours is used for the estimated annual operating time.

Average annual replacement parts cost for all Model EN (12.0 MeV) accelerators in use, based on our replacement part sales figures, is $25,000.00.

Average operating time for most EN machines is approximately 5000 hours which gives an operating replacement part cost/hour of $5.00.

The following calculations show that the High Energy - High Intensity Tandem proposed for Ohio University compares reasonably well with the EN figures.

Using an assumed 5000 hours/annum:

1. Power $5000 \times 50 \times 10^3 = 25 \times 10^7$

$= 25 \times 10^4$ kw-hr

assume 1.0¢/kw-hr = $2,500.00

2. Foils - 20 hrs/foil

$\frac{5000}{20} = 250$ foils required

$\frac{250}{64} = 4$

4 x $25.00 = $ 100.00

3. Charging Belt worst case 1/year $ 555.00

4. Tubes, 1/2 set/annum $ 30,000.00

5. Cathodes - use 100 hours assumed life

$\frac{5000}{100} = 50$ cathodes

at $30.00 each

30 x 50 = $ 1,500.00

Annual 5000 hr cost $34,655.00

Therefore: cost per hour is

$\frac{34,655}{5000} = \$6.93$

APPENDIX

MEMO

TO: Distribution

FROM: A. Galejs

DATE: January 2, 1968

SUBJECT: T8-Tandem Optics

The T8-Tandem performance has been calculated previously under various assumed initial and operating conditions. The present calculations have been done as part of the Ohio University sales proposal, in order to predict the tandem performance with the specific diode source injector arrangement, as well as to provide the input information for designing the post-acceleration beam-handling system.

Figure 1 shows the beam emittance from the diode source in the (X, X^1) - and (Y, Y^1) - planes at a point 72.0 inches from the acceleration tube, or more specifically, from the tube entrance grid. It is assumed that the reasons for focusing in the manner shown are spelled out elsewhere. The difference in the phase-space contours is brought about by the astigmatism of the inflection magnet. While one could have assumed an emittance contour which encompasses both contours shown, in the present case, each plane has been traced through separately all the way to the target.

Figure 2 shows how the acceptance has been calculated of a 36.0" by 0.375" stripper canal. This represents the smallest restriction in the accelerating system. Figures 3A, B and 4A, B show a typical maximum beam envelope through the accelerator. They are only given for the terminal potential of V_T = 2.5 MV since particularly in the low energy tube, the trajectories are similar for all terminal voltages considered. It should be noted that the max. beam diameter in all cases is of the order of 1.6 inches in diameter. The beam in practice is obviously focused at the center of the stripper canal for maximum transmission - its phase-space representation is (X, X^1) - and (Y, Y^1)- planes is shown in Figure 5A. In order to achieve the desired pulsed width, the klystron buncher introduces an energy spread of ± 5 keV for the proton and ± $5/\sqrt{2}$ keV or ± 3.54 keV for the deuteron beam. Since the entrance grid bi-potential lens will be adjusted to focus the 80 keV beam at the stripper canal, the energy spread introduced by the buncher results in an effective chromatic error - the effect of this error is also seen in Figure 5A, and furthermore, transferred to the end of the accelerator, shown in Figures 5B and 5C. The deuteron case for V_T = 2.5 MV is similarly represented in Figures 6A, B and C.

The groups of Figures (7,8) (9, 10) and (11, 12) are simply calculations for V_T = 4.0, 1.0 and 5.5 MV respectively. It should be noted that for all terminal potentials, the beam from the diode source has been transmitted 100% through the accelerator - this is seen on the "A" diagrams of all cases above - the acceptance of the stripper canal has been entered as the dotted contour. Only in the V_T = 1.0 MV case, some minor clipping is indicated in the canal. (See Figure 9A). However, it is seen upon inspection, that by adjusting the gridded lens voltage V_L, the effective emittance areas could have been centered within the stripper acceptance.

In order to provide realistic information for designing the subsequent post-acceleration beam-handling system, Figures 13 to 16 have been used. The oblique parallelograms shown on all of these contours represent the smallest phase-space areas which the beam occupies in presence of the energy spread introduced by the buncher. The present report is intended to provide the input information for designing the beam-handling system. All graphs are labeled explicitly and are almost self-explanatory.

The discussion of the specific beam-handling system proposed is subject of a subsequent discussion and will not be touched upon here.

A. G.

A. Galejs
January 2, 1968

AG/nh

APPENDIX IV

<u>Sample Beam Handling Computer Print-outs:</u>

Reproduced print-out is for a 5.0 MeV pulsed ion beam of protons. Information shown is beam envelope characteristics at the entrance, middle position, and exit of each optical component or critical location in the beam handling system.

The following envelope information was used to plot the illustration in section 3.0.0:

X	X^1	Y	Y^1	Component
Leaving start to 30.67"				
.3400	.003400	.3000	.003300	
.5000	.003400	.4800	.003300	
Entering #1 OD 11.400 .05910 from 30.67" window 1.0000 / 1.0000				1
.4443	.003400	.4012	.003300	
.6043	.003400	.5812	.003300	
Leaving #1 OD 11.400 .05910 to 3.60" window 1.0000/ 1.0000				2
.5907	.023261	.3484	-.012215	
.7885	.030125	.4891	-.018852	
Entering #2 OC 11.400 .06343 from 3.60" window 1.0000/ 1.0000				
.6745	.023261	.3044	-.012215	
.8969	.030125	.4212	-.018852	

X	X^1	Y	Y^1	Component
Leaving # 2 OC 11.4000 .06343 to 64.00" window 1.0000/ 1.0000				3
.7484	-.010870	.2358	-.000339	
.9867	-.015059	.3020	-.002953	
Entering # 3 check pt. from 64.00" window .1000/ 1.0000				
.0527	-.010870	.2141	-.000339	
.0229	-.015059	.1130	-.002953	
Entering # 4 Mag (0.) 45.000 .000 .000 28.000 .00000 from 28.00" window 1.2500/ .5000				4
-.2517	-.010870	.2046	-.000339	
-.3987	-.015059	.0303	-.002953	
Leaving # 4 Mag (0.) 45.000 .000 .000 28.000 .00000 to .00" window 1.2500/ .5000				
-.3932	-.001330	.1972	-.000339	
-.5801	-.000579	-.0346	-.002953	
Entering # 5 check pt from .00" window 1.2000/ .5000				5
-.3932	-.001330	.1972	-.000339	
-.5801	-.000579	-.0346	-.002953	
Entering # 6 Mag (0.) 45.000 .000 .000 28.000 .00000 from .00" window 1.2500/ .5000				6
-.3932	-.001330	.1972	-.000339	
-.5801	-.000579	-.0346	-.002953	
Leaving # 6 Mag (0.) 45.000 .000 .000 28.000 .00000 to 28.00" window 1.2500/ .5000				
-.3044	.008988	.1897	-.000339	
-.4217	.014240	-.0996	-.002953	

X	X^1	Y	Y^1	Component
Entering # 7 check pt. from 28,00"				7
window .1000/ 1.0000				
-.0527	.008988	.1802	-.000399	
-.0229	.014240	-.1822	-.002953	
Entering # 8 Mag (0.) 22.500 .000 .000 33.000 .00000 from 56.00"				
window 1.2500/ .5000				8
.4507	.008988	.1612	-.000339	
.7745	.014240	-.3476	-.002953	
Leaving # 8 Mag (0.) 22.500 .000 .000 33.000 .00000 to .00"				
window 1.2500/ .5000				
.5299	.003078	.1568	-.000339	
.8954	.004175	-.3859	-.002953	
Entering # 9 check pt. from .00"				9
window 1.2500/ .5000				
.5299	.003078	.1568	-.000339	
.8954	.004175	-.3859	-.002953	
Entering #10 Mag (0.) 22.500 .000 22.500 33.000 .00000 from .00"				
window 1.2500/ .5000				
.5299	.003078	.1568	-.000339	
.8954	.004175	-.3859	-.002953	
Leaving #10 Mag (0.) 22.500 .000 22.500 33.000 .00000 to 63.00"				
window 1.2500/ .5000				10
.5284	.003332	.1524	-.002252	
.8799	.004518	-.4242	.002371	
Entering #11 OC 11.700 .05169 from 63.00"				
window 1.3000/ 1.3000				
.7383	.003332	.0105	-.002252	
1.1646	.004518	-.2748	.002371	
Leaving # 11 OC 11.700 .05169 to 3.30"				11
window 1.3000/ 1.3000				
.6440	-.018958	-.0155	-.002327	
1.0077	-.030510	-.2971	-.006306	

X	X¹	Y	Y¹	Component
Entering #12 OD 11.700 .05256 from 3.30" window 1.3000/ 1.3000				
.5814	-.018958	-.0232	-.002327	
.9070	-.030510	-.3180	-.006306	
Leaving #12 OD 11.700 .05256 to 140.00" window 1.3000/ 1.3000				12
.4588	.002656	-.0445	-.001199	
.7041	.005262	-.3289	.004491	
Entering #13 check pt. from 140.00" window .1000/ .3000				13
.0869	-.002656	-.2123	-.001199	
-.0326	-.005262	.2998	.004491	
Entering # 1 QD 11.700 .06122 from 108.00" window 2.0000/2.0000				14
-.1999	-.002656	-.3418	-.001199	
-.6009	-.005262	.7848	.004491	
Leaving # 1 QD 11.700 .06122 to 3.30" window 2.0000/2.0000				
-.2873	-.012904	-.2707	.012834	
-.8287	-.035332	.6481	-.028159	
Entering # 2 QC 11.700 .06669 from 3.30" window 2.0000/ 2.0000				15
-.3299	-.012904	-.2283	.012834	
-.9453	-.035332	.5472	-.028159	
Leaving # 2 OQ 11.700 .06669 to 51.87"				
-.3706	.006304	-.1355	.003821	
-1.0445	.019238	.3585	-.005722	
Entering finish from 51.87" window 2.0000/ 2.0000				
-.0436	.006304	.0626	.003821	
-.0467	.019238	.0617	-.005722	

APPENDIX VI

Biographical data is included for:

Dr. John G. Trump	-	Chairman of the Board
Dr. Dennis M. Robinson	-	President
Charles H. Goldie	-	HVEC Staff
Robert A. Fernald	-	HVEC Staff
Robert R. Charpentier	-	HVEC Staff
Annija D. Galejs	-	HVEC Staff
Dr. Harold A. Enge	-	Consultant
Robert W. Cloud	-	Consultant
Dr. Peter H. Rose	-	HVEC Staff
Dr. Andrew B. Wittkower	-	HVEC Staff
Dr. Sam V. Nablo	-	IPC Staff
Dr. A.S. Denholm	-	IPC Staff
Dr. Michael J. Mulcahy	-	IPC Staff

DR. JOHN G. TRUMP

Chairman of the Board and Technical Director

Education

B.S., Polytechnic Institute of Brooklyn, 1929
M.S., Columbia University, 1931
D.Sc., Electrical Engineering, Massachusetts Institute of Technology, 1933

Professional Experience

1946-present	Chairman of the Board and Technical Director, High Voltage Engineering Corporation
1952-present	Professor, Electrical Engineering Department, Massachusetts Institute of Technology
1936-present	Director of High Voltage Research Laboratory, Massachusetts Institute of Technology
1944-45	Wartime Director, British Branch, Radiation Laboratory, Massachusetts Institute of Technology
1942-44	Secretary and Technical Advisor, Radar Division 14, Office of Science Research and Development
1940-42	Technical Advisor, National Defense Research Committee, Div. D. (Radar, Fire-control, Instruments, Infra-rad)
1941-52	Associate Professor, Electrical Engineering Department, Massachusetts Institute of Technology
1936-41	Assistant Professor, Electrical Engineering Department, Massachusetts Institute of Technology
1933-36	Research Associate, Massachusetts Institute of Technology
1929-31	Instructor, Electrical Engineering, Polytechnic Institute of Brooklyn

Awards

1946	Decorated with His Majesty's Medal (England)
1946	Citation (Presidential)
1961	Lamme Medal for 1960
1963	Public Service Award - Brooklyn Polytechnic Alumni Association (outstanding service to education)

Publications

"Thermocouple Gauge for Vacuum Measurement," G. C. Dunlap, J. G. Trump, R. S. I. 8, No. 1, p. 37-38, Jan. 1937

"Design of a Million-Volt X-Ray Generator for Cancer Treatment and Research," J. G. Trump, R. J. Van de Graaff, J. of Appl. Phys. 8, p. 602-606, Sept. 1937

"Production of Supervoltage Roentgen Rays by Means of an Electrostatic Generator," R. Dresser, J. G. Trump, R. J. Van de Graaff, Am. J. of Roent. & Rad. Therapy 38, No. 5, p. 758-761, Nov. 1937

"Van de Graaff Generator for General Lab. Use," J. G. Trump, F. H. Merrill, F. J. Safford, R. S. I. 9, No. 12, p. 398-403, Dec. 1938

"A Compact Pressure-Insulated Electrostatic X-Ray Generator," J. G. Trump, R. J. Van de Graaff, phys. Rev. 55, p. 1160-1165, June, 1939

"Generating Voltmeter for Pressure-Insulated High Voltage Sources," J. G. Trump, F. J. Safford, R. J. Van de Graaff, R. S. I. 11, No. 2, p. 54-56, Feb. 1940

"Cathode Rays for Radiation Therapy," J. G. Trump, R. J. Van de Graaff, R. W. Cloud, Am. J. of Roent. & Rad. Therapy 43, No. 5, p. 728-734, May, 1940

"Compact, Supervoltage, Roentgen-Ray Generator Using a Pressure-Insulated Electrostatic High Voltage Source," J. G. Trump, R. J. Van de Graaff, R. W. Clous, Am. Jo. of Roent. & Rad. Therapy 44, No. 4 p. 610-614, Oct. 1940

"Physical Characteristics of Supervoltage Roentgen Rays," J. G. Trump, R. W. Cloud, Am. Jo. of Roent. & Rad. Therapy 44, No. 4, p. 615-618, Oct. 1940

"D-C Breakdown Strength of Air and of Freon in a Uniform Field at High Pressures," J. G. Trump, F. J. Safford, R. W. Cloud, Elec. Eng. Trans. 60, No. 3, p. 132-134, March, 1941

"High Voltage D-C Flashover of Solid Insulators in Compressed Nitrogen," J. G. Trump, J. Andrias, Elec. Eng. Trans. 60, No. 11, p. 986-989, November, 1941

Publications (continued)

"The Production and Characteristics of 3,000 Kilovolt Roentgen Rays," J. G. Trump. R.W. Cloud, Am. Jo. of Roent. & Rad. Therapy 49, No. 4, p. 531-535, April 1943

"The Insulation of High Voltages in Vacuum," J.G. Trump, R.J. Van de Graaff, Jo. of Appl. Phys. 18, No. 3, p. 327-332, March, 1947

"Electrostatic Sources of Electric Power," J.G. Trump, Elec. Eng. 66, No. 6, P. 525-534, June 1947

"Efficient Deep Tumor Irradiation with Roentgen Rays of Several Million Volts," J.G. Trump, C.R. Moster, R.W. Clous, Am. Jo. of Roent. & Rad. Therapy 57, No. 6, p. 703-710, June 1947

"Roentgen Rays Against Cancer," J.G. Trump, Tech. Review 50, No. 2, p. 91-95, Dec. 1947

"Physical Basis for High Skin Tolerance of Supervoltage Roentgen Rays," J.G. Trump, Radiology 50, No. 5, p. 649-656, May 1948

"Irradiation of Biological Materials by High Energy Roentgen Rays and Cathode Rays," J.G. Trump, R.J. Van de Graaff, Jo. of Appl. Phys. 19, No. 7, p. 599-604, July 1948

"Electrostatic Generators for the Acceleration of Charged Particles," R.J. Van de Graaff, J.G. Trump. W.W. Buechner, Reports on Progress in Physics (Brit.), Vol. XI p. 1-18, 1948

"Secondary Emission of Electrons by High Energy Electrons," J.G. Trump, R.J. Van de Graaff, Physical Rev. 75, No. 1 p. 44-45, Jan. 1949

"The Protection of Personnel Engaged in Roentgenology and Radiology," F.T. Hunter, O.E. Merrill, J.G. Trump, L.L. Robbins, New Eng. Jo. of Med. 241, p. 79-89, July 21, 1949

"Effect of High Voltage Electrical Discharges on Sulfur-Hexafluoride," W.C. Schumb, J.G. Trump, G.L. Priest, Industrial & Eng. Chem. 41, p. 1348-1351, July 1949

"Distribution of Ionization in Materials Irradiated by 2- and 3-Million Volt Cathode Rays," J.G. Trump, K.A. Wright, A.M. Clarke, Jo. of Appl. Phys. 21, No. 4, p. 345-348, April 1950

Publications (continued)

"Influence of Electrodes on D-C Breakdown in Gases at High Pressure," J.G. Trump, R. W. Cloud, J.G. Mann, E.P. Hanson, Elec. Eng. 69, No. 11, p. 961-964, Nov. 1950

"Physical and Clinical Aspects of Supervoltage Rotational Therapy," J.G. Trump, H.F. Hare, et al, Radiology, 57, No. 2, p. 157-167, 1951

"Electrostatic Sources of Ionizing Energy," J.G. Trump, AIEE Transactions, Vol. 70, 1951

"Two-Million Volt Roentgen-Ray Therapy Using Rotation," J.G. Trump, H.F. Hare, et al, Am. Jo. of Roent. & Rad. Therapy, Vol. 66, No. 4, October, 1951

"Electron Sterilization," J.G. Trump, Machlett Cathode Press, Winter Issue 1950-51

"Sterilizing with Electrons," J.G. Trump. B.E. Proctor, Modern Packaging Magazine, July, 1951

"Rotational Scanning of Breast Malignancies with Supervoltage Radiation," J.G. Trump, H.F. Hare, E.W. Webster, Am. Jo. of Roent. & Rad. Therapy Nu. Med. Vo. 68, No. 3, Sept. 1952

"Absorption of 2 MeV Constant Potential Roentgen Rays by Lead and Concrete," J.G. Trump, et al, Radiology, Vol. 58, No. 4, pp. 560-67 April, 1952

"Secondary Electron Emission From Metals Under Positive Ion Bombardment in High Extractive Fields," J.G. Trump, R.J. Van de Graaff, E.W. Webster, Jo. of Appl. Phys., Vo. 23, No. 2, 264-266, Feb. 1952

"High Energy Electrons for the Treatment of Extensive Superficial Malignancies," J.G. Trump, et al, Am. Jo. of Roent. & Rad. Therapy, Vol. LXIX No. 4, April, 1953

"Treatment of Tumors of the Pelvic Cavity with Supervoltage Radiation," J.G. Trump, etal, Amer. Jo. Roent. & Rad. Therapy, August 1954

"The Film Method of Tissue Dose Studies with 2.0 MeV X-Rays," J.G. Trump, et al, Am. Jo. of Roent. & Rad. Therapy, Vol. LXXII, No. 2., August 1954.

Publications (continued)

"Radiation Therapy for Bronchogenic Carcinoma," J. G. Trump, et al, Geriatrics, October 1953, Vol. 8, No. 10

"Cathode Ray Treatment for Lymphomas Involving the Skin," J. G. Trump, et al, A. M. A. Archives of Dermatology and Syphilology, Vol. 68, pp. 635-642, December 1953

"Observations on Rotational Therapy with 2 Million Volt Roentgen Rays," J.G. Trump, et al, Jo. of Am. Med. Assoc., Vol. 154, pp. 890-894, March 1954

"Electron Emission from Metals Under High Energy Hydrogen Ion Bombardment," J.G. Trump, B. Aarset, R.W. Cloud, Jo. of Appl. Phys. Vol.25, No. 11, pp. 1365-1368, November, 1954

"Radiographic Properties of X-Rays in the Two to Six Million Volt Range," J.G. Trump et al, ASTM Bulletin, No. 201, October 1954

"High Energy Electrons for Generalized Superficial Dermatoses," J.G. Trump, et al, A.M.A. Archives of Dermatology, Vol. 71, March 1955

"Role of Positive Ions in High-Voltage Breakdown in Vacuum," J. G. Trump, H.C. Bourne, Jr., R.W. Cloud, Jo. of Appl. Phys. Vol. 26, No. 5, pp, 596-599, May, 1955

"The Clinical Use of Cathode Ray Sterilized Grafts of Cadaver Bone," J. G. Trump et al, Vol. VI "Surgical Forum" 1956

"Physical Aspects of Megavolt Electron Therapy," J. G. Trump, K. A. Wright, R. C. Granke, Radiology, Vol. 67, No. 4, October 1956

"Inactivation of the Hepatitis Virus by High Energy Electrons," J.G. Trump, K.A. Wright, Reprinted from Hepatitis Frontiers, Internat. Sympos. Henry Ford Hosp. Detroit, Michigan, Pub. 1957

"Sterilization of Preserved Bone Grafts by High Voltage Cathode Irradiation," J.G. Trump et al, Reprinted from Jo. of Bone & Joint Surgery, Vol. 38-A, No. 4, pp. 862-884, July 1956

"Barium Absorption Pumps for High Vacuum Systems," J. G. Trump, R.W. Cloud, L. Beckman, Rev. of Sci. Instr. Vol. 28 No. 11 pp 889-892, November, 1957

Publications (continued)

"High Energy Electrons for the Irradiation of Blood Derivatives," J.G. Trump, K. A. Wright, Bibliotheca Haematologica Proc. of Sixth Congress of Internat. Soc. of Blood Transfusion, Boston Sept. 3 - 5, 1956

"Electron-Irradiated and Freeze-Dried Arterial Homografts," J. G. Trump et al, Annals of Surgery, Vol. 147, No. 4 April, 1958

"Two-Million-Volt X-Ray Therapy of Hodgkin's Disease," J. G. Trump, Hare, Dahle, Annals of the New York Acad. of Sci. Vol. 73, Art. 1, pp. 363-371, September, 1958

"Field Shaping and Selective Protection in Megavolt Radiation Therapy," J. G. Trump et al, Radiology, Vol. 72, No. 1, p. 101, January, 1959

"Physical Aspects of Two Million Volt X-Ray Therapy," J. G. Trump, K. A. Wright, B.S. Proimos, The Surgical Clinics of No. America, Vol. 39, No. 3, pp, 567-578, June 1959

"Electron Beam Therapy of Widespread Superficial Malignant Lesions," J. G. Trump et al, The Surgical Clinics of No. America, Vol. 39, No. 3, pp 579-584, June 1959

"Roentgen Rays: Supervoltage Apparatus," J.G. Trump, "Medical Physics, Vol. 3, Year Book 1960, pp. 590-591

"Supervoltage Radiation Therapy in the Next Decade," J.G. Trump, The Surgical Clinics of No. America. Vol. 40, No. 3, pp. 839-848, June 1960

"Modification of Strontium 90 Emission for Superficial Therapy," Trump, Proimos and Wright, Brit. Jo. of Radiology, Vol. XXXIII, No. 394, pp. 640-643, October 1960

"Synchronous Field Shaping and Protection in 2 Million Volt Rotational Therapy," J.G. Trump et al, Radiology, Vol. 76, No. 2., Feb. 1961

"High Energy Electrons for the Sterilization of Surgical Materials," John G. Trump, Reprinted from Sterilization of Surgical Materials Symposium, April 11-13, 1961

"Management of Lymphoma Cutis with Low Negavolt Electron Beam Therapy," J.G. Trump, et al, Southern Medical Jo. of the So. Med. Assoc. Vol. 54, No. 7, pp. 769-776, July 1961

Publications (continued)

"On the Possibilities of Rotating Vacuum-Insulated Electrostatic Machinery," J. G. Trump, Editions Du Centre Nat. de la Recherche Scientifique Quai Anatole-France-Paris, VII, 1961

"Surgery and Supervoltage Therapy in the Treatment of Carcinoma of the Lung," J.G. Trump et al, Jo. of the Amer. Med. Assoc. Vol. 179, pp. 253-256, January, 1962

"Back-Scattering of Megavolt Electrons from Thick Targets," K. H. Wright, J. G. Trump, Jo. of Appl. Physics Vol. 33, No. 2, 687-690, Feb. 1962

"Ten Year Experience with Low Negavolt Electron Therapy," J. G. Trump, et al, The Am. Jour. of Roent, & Rad. Therapy and Nu. Med., Vol. LXXXVIII No. 2, August 1962

"Concepts of Fixed and Variable Fields in Megavolt Radiotherapy," J. G. Trump, et al,

"Compressed Gas Insulation and Electric Power Systems," J. G. Trump, Reprinted from "Gas Discharges and the Electricity Supply Industry" Proceedings of the Internat. Conf. Cent. Electricity Res. Lab. Leatherhead, Surrey, Eng., May 1962 - Butterworths

"Two Million Volt Radiation in the Treatment of Localized Lymphoma," J.G. Trump, J.W. Norcross, D.O. Johnston, Proceedings of the VIIIth Internat. Congress of Hematology, Tokyo, September 4 - 10, 1960

"Megavolt Xeroradiography," J.G. Trump, K.A. Wright, J.L. DuBard, Radiology, Vol. 80, No. 1, p. 118, January, 1963

"Radiation for Therapy - In Retrospect and Prospect," J. G. Trump, Am. Jo. of Roent., Rad. Therapy & Nu. Med., Vol. XCI, No. 1 pp. 22-30 1964

"Two MeV Wide Field Irradiation of Lymphoma: Twelve Year Experience," J.G. Trump et al, Am. Jo. of Roent., Rad. Therapy & Nu. Med. Vol. XCII, No. 1, July 1964

"High Gradient Studies for Accelerator Systems," J.G. Trump, Nu. Instr. & Methods, 28, pp. 10 - 15, 1964

"Insulation of High Voltage Across Solid Insulators in Vacuum," J.G. Trump et al, Internat. Symp. on Insul. of High Volt. in Vac. Kresgie-Oct. 19-21, 1964 Jo. of Vac. Sci. & Tech. Vol. 2, No. 5, pp. 234-239 Sept./Oct. 1965

Other Affiliations

Fellow American Physical Society
Fellow American Institute of Electrical and Electronic Engineers
Assoc. Member New England Roent. Ray Society
Assoc. Member American Roent. Ray Society
Member American Radium Society
Fellow American Academy Arts & Sciences
American Association of Physicists of Medicine
Scientific Advisory Committee - Damon Runyon Memorial Fund
Nucleonics Committee of the I. E. E. E.
Senior Thesis Committee - M. I. T.
Committee on Graduate Admissions and Fellowships - M. I. T.
Ad Hoc - Biomedical Engineer - M. I. T.
Trustee of Lahey Clinic Foundation and Senior Research Associate in Physics

DENIS MORRELL ROBINSON

President

Education

King's College, London - Siemen's Prize 1st Class Honours in Electrical Engineering, B.Sc. (Eng.), 1927

University of London Postgraduate Studentship 1928-29 Ph.D. 1929.

Commonwealth Fund Fellowship, Massachusetts Institute of Technology, electrical engineering, S.M., 1931

Professional Experience

1946-present	President of High Voltage Engineering Corporation, Burlington, Massachusetts
1945-46	Professor of Electrical Engineering and Head of Department, University of Birmingham, England
1941-45	Staff Member, Radiation Laboratory, Massachusetts Institute of Technology, and British Representative
1939-41	Telecommunications Research Establishment, Ministry of Aircraft Production
1935-39	Research Engineer, Scophony Television Laboratories, London
1931-35	Research Engineer, Callender's Cable & Construction Company, Limited, London. Also lecturer and demonstrator, Northampton and Regent Street Polytechnic schools.

Awards

1946	U. S. Medal of Freedom with Bronze Palm
1946	Order of the British Empire

Publications

"Dielectric Phenomena in High Voltage Cables" 1936

Articles in "Journal of the Institution of Electrical Engineers," "Proceedings of the Institute of Radio Engineers," "Nucleonics," "Physics"

Other Affiliations

Director, Harvard Trust Company, Cambridge, Massachusetts
Director, Associated Industries of Massachusetts
Member of the Raad van Commissarissen, High Voltage Engineering (Europa) N. V., Amersfoort, The Netherlands
Member of the Visiting Committee to the MIT Department of Sponsored Research
Member of the Committees to Visit the Departments of Engineering & Applied Physics and Physics at Harvard University
Fellow of Branford College, Yale University
Fellow of American Academy of Arts and Sciences
Fellow of American Physical Society
Member, Institution of Electrical Engineers, London

CHARLES H. GOLDIE

Manager of Operations, Accelerator Division

Education

S. B. in Physics, Massachusetts Institute of Technology, 1945

S. M. in Physics, Massachusetts Institute of Technology, 1953

Professional Experience

1955-present — High Voltage Engineering Corporation. Manager of Operations, Accelerator Division. Since joining High Voltage Engineering Corporation in 1955, C. H. Goldie has worked on particle accelerator systems and their applications. He successfully led and completed the development of a "miniaturized" particle accelerator using a sealed acceleration tube for the production of neutrons from the T(d, n) He^4 reaction - an accelerator used in subsurface exploration. One of his principal research programs has been the investigation of various vacuum, pressure, and solid insulated electrostatic generators. These investigations have led to a number of experiments concerning the insulators volume puncture strength and surface flash-over properties. He has contributed to the development of particle accelerator components, notably ion sources, and currently has overall responsibility for product improvement programs including the setting up of statistical testing methods and design experiments.

He has developed application techniques for ion and electron particle accelerators. These include neutron activation analysis, deuteron surface activation and supervoltage X-rays for industrial radiography.

1952-53 — Massachusetts Institute of Technology, Electrical Engineering Department. Research Assistant. Measurements of the properties of 2 to 6 MeV X-ray to determine feasibility of radiographic applications.

1946-52 — Massachusetts Institute of Technology, Laboratory of Nuclear Science and Engineering. Staff Member. Development of Van de Graaff Particle Accelerator for nuclear research and X-ray production.

1945-46 — Ensign U. S. N. R. Assistant Engineering Office, Large Auxiliary Ships.

CHARLES H. GOLDIE (Cont.)

Professional Affiliations

American Physical Society
American Rocket Society
American Nuclear Society

Publications

Papers in Particle Accelerator Applications High Voltage X-Rays

Fields of Special Interest

High Vacuum Techniques
High Voltage Electrostatics
Ion Sources and Emitters
Particle Acceleration and Optics
Radiations and Nuclear Phenomena

ROBERT A FERNALD

Director of Project Management, Accelerator Division

Education

B.S. Elec. Eng., University of Maine, 1954
M.S. without specification, Massachusetts Institute of Technology, 1954-56.

Professional Experience

1959- present	High Voltage Engineering Corporation. Burlington, Mass. Director of Project Management, Accelerator Division.
1956-59	High Voltage Engineering Corporation, Physicist
1954-56	High Voltage Engineering Corporation, Research Assistant

Professional Affiliations

Radio Institute of Electrical Engineers
American Rubber Society
American Chemical Society

Fields of Special Interest

Charging systems
Ion source development
Dielectrics of plastics
Nanosecond compression systems

Experience

R. A. Fernald has been primarily concerned with investigations in the general field of electrical breakdown of plastic insulators and other materials and charging systems for electrostatic machines. His experience in the properties of plastic insulators has enabled him to develop elastomer formulations with tailored electrical properties for accelerator control elements. In addition, R. A. Fernald has made many contributions to ion source technology, having done his M.S. thesis work in this field.

Publication

"Production of High Intensity Ion Pulses of Nanosecond Duration", Fernald, R. A. and Hahn, F.S., Nuclear Instruments and Methods 12, 335-40, 1961.

ROBERT R. CHARPENTIER

Project Manager, Accelerator Division

Education

Chemical Engineering Degree, and B.B.A at Northeastern University

Professional Experience

Oct. 1962- present	High Voltage Engineering Corporation, Accelerator Division. Project Manager. Responsible for research, test and development of hign voltage devices. These activities include the feasibility of organic polymers and elastomers as mechanical and electrical insulators. The test equipment includes: the operation of high voltage test equipment, tensile and compression test devices and test devices related to the evaluation of fabricated polymeric structures.
July 1955- Oct 1962	Massachusetts Institute of Technology, High Voltage Research Laboratory of the Electrical Engineering Department. Engineering Assistant. Activities there combined research, engineering and management. Most of the programs were directed towards the thesis work of students assigned to our facilities. The direction of activities were in the following programs: development of an externally heated barium getter pump, development of an induction-conduction belt for Van de Graaff generators, cold cathode emitting device for demonstration at the Museum of Science, spectrometric analysis of vacuum tubes, the production of electrodes for study of high currents in vacuum, solid insulation studies in high pressure and in vacuum, development and production of X-ray tubes, electron tubes and Van de Graaff generator belts, the study of insulating films under high field conditions, polymerization studies on paints and polymers using ionizing electron beam, development of an electrostatic paint spraying generator of Van de Graaff type, development of a semiconducting glass tandem generator and formulation and production of polymer structures.
Sept 1951- July 1955	Cambosco Scientific Company. Production Manager for a small instruments manufacturer of secondary school laboratory equipment. This function included cost analysis work, expediting, quality control, purchasing, time study, inspection and supervision. Frequently, the need to re-design and engineer new equipment plus the attendance of conventions on company matters was made part of his duties.
July 1946 Sept 1951	U.S. Army and Special duty with the State Department in Rio de Janeiro, Brazil.

ANNIJA D. GALEJS

Head of the Mathematical Physics Section

Education

Physics, University of Tubingen, Germany, 1948-1949

S.B. in Mathematics, University of Chicago, 1953

M.S. in Physics, Illinois Institute of Technology, 1955

Ph.D., Illinois Institute of Technology. Comprehensive Examinations passed in 1957

Special Training

FORTRAN Automatic coding course for the IBM 704 computer (at General Electric, 1960). Basic programming course for the PHILCO 2000 computer (at AVCO, 1960).

Professional Experience

1959-present — High Voltage Engineering Corporation, Research Tandem Group. Mathematical Physicist. A. Galejs joined HVEC to work in the field of applied mathematics. In addition to an extensive and thorough training in mathematics, her academic background included work on space charge problems and electron optics. Her previous industrial employment was in the field of solid state physics, with emphasis on research and development of transistors and semiconductor space charge devices. Current projects included exact ion trajectory calculations in accelerator tubes using IBM 704 computer and conceptual study of accelerating and focusing system design. Her background in both mathematics and physics enables her to lend effective support to our applied and experimental work.

1957-58 — Raytheon Manufacturing Company, Research Division, Waltham, Mass. Physicist.

1955-56 — Zenith Radio Corporation, Chicago, Illinois. Physicist.

Publications

"Potential Distribution as a Function of Current in the Spherical Diode," Jour. Appl. Phys., 26, p. 779, 1955.

HARALD A. ENGE

Consultant

Current Assignment

Associate Professor of Physics, Laboratory of Nuclear Science, M. I. T. and Consultant to HVEC.

Education

Ph. D., University of Bergen, 1952

Fields of Special Interest

Heavy-particle spectroscopy
Design of charged-particle spectrographs and spectrometer
Ion optics
Design of ion optical equipment

Publications

H. A. Enge, "Combined Magnetic Spectrograph and Spectrometer," Rev. Sci. Instrum., 29, No. 10, 885-8 (Oct. 1958).

H. A. Enge, "Ion Focusing Properties of a Quadrupole Lens Pair," Rev. Sci. Instrum., 30, No. 4, 248-51 (April 1959).

H. A. Enge, E. J. Irwin, Jr., and D. H. Weaner, "Results of Stripping Analysis of the Reaction K^{39} (d, p) K^{40} Phys. Rev., 115, No. 4, 949-55 (Aug. 15, 1959).

H. A. Enge, D. L. Jarrell and C. C. Angleman, "Results of Stripping Analysis of the Co^{59}(d, p) Co^{60} Reaction," Phys. Rev., 119, No. 2, 735-40 (July 15, 1960).

H. A. Enge, "Ion Focusing Properties of a Three-Element Quadrupole Lens System," Rev. Sci. Instrum., 32, No. 6, 662-6 (June 1961).

J. R. Erskine, W. W. Buechner and H. A. Enge, "Bi^{209}(d, p)Bi^{210} Reaction at Low Bombarding Energies and with High Resolution," Phys. Rev., 128, No. 2, 720-8 (Oct. 15, 1962).

H. A. Enge and W. W. Buechner, "Multiple-Gap Magnetic Spectrograph for Charged Particle Studies," Rev. Sci. Instrum., 34, No. 2, 155-62 (Feb. 1963).

H. A. Enge, "Achromatic Magnetic Mirror for Ion Beams," Rev. Sci. Instrum., 34, No. 4, 385-9 (April 1963).

ROBERT W. CLOUD

Consultant

Education

B.S., Denver University
B.S., M.S., Massachusetts Institute of Technology (EE)

Professional Experience

1946-present	Research Associate in High Voltage Lab., MIT., working with the development of the Van de Graaff generator and high vacuum tubes.
1938-46	High Voltage Research Lab., MIT, Research Assistant.

Fields of Special Interest

Electrostatic high voltage sources
Compressed gas insulation
Properties of high energy particles and radiations

Publications

"D. C. Breakdown Strength of Air and of Freon in a Uniform Field at High Pressures," Trump, J. G., Safford, F. F. and Cloud, R. W., Elec. Eng. Trans. 60, No. 3, p. 132-134, March, 1941.

"Vacuum Tests of Rubber, Lead, and Teflon Gaskets and Vinyl Acetate Joints," Cloud, R. W. and Philip, S. F., Rev. of Sci. Instr. 21, No. 8, 731-733, Aug., 1950.

"Electron Emission from Metals under High Energy Hydrogen Ion Bombardment," Aarset, B., Cloud, R. W. and Trump, J. G., Jour. Appl. Phys. 25, No. 11, 1365-1368, November, 1954.

"Radiographic Properties of X-rays in the Two to Six Million Volt Range," Goldie, C. H., Wright, K. W., Anson, J. H., Cloud, R. W., and Trump, J. G., ASTM Bulletin No. 201, 49-54, October, 1954.

"Role of Positive Ions in High-Voltage Breakdown in Vacuum," Bourne, H. C. Jr., Cloud, R. W. and Trump, J. G., Jour. Appl. Phys. 26, No. 5, 596-599, May, 1955.

"Barium Absorption Pumps for High Vacuum Systems," Cloud, R. W., Beckman, L, and Trump, J. G., Rev. Sci. Instrum. 28, No. 11, 889-892, Nov. 1957.

Also, papers in the fields of special interest listed above.

PETER H. ROSE

Present Position

Vice President and Director of Research in the Robert J. Van de Graaff Laboratory, High Voltage Engineering Corporation, Burlington, Massachusetts.

Education

B. Sc., King's College, London, England, 1943-1945
Ph. D., University of London, London, England, 1945-1955

Publications

Review Articles

"Optics of Electrostatic Accelerator Tubes". A. Galejs and P. H. Rose; Focusing of Charged Particles; Ed. A. Septier (Academic Press, Inc., New York), 1967.

"The Production and Acceleration of Ion Beams in the Tandem Accelerator"; P. H. Rose and A. Galejs; Progress in Nuclear Techniques; ed. F. J. M. Farley (North-Holland Publishing Co., Amsterdam), Vol. 2, (1967).

Invited Papers

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Publications

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B.Sc., 1955, 1st class Honors in Mathematics and Physics
McGill University, Montreal, Canada

M.Sc., 1959, University of Cambridge, England
Province of Quebec, Postgraduate Research
Scholarship, 1957-1959

Ph.D., 1967, University College, London, England

Professional Experience

1967 - Present	Assistant Director of Research in the Robert J. Van de Graaff Laboratory, High Voltage Engineering Corporation, Burlington, Massachusetts
1965-67	Honorary Research Assistant, University College, London, England
1959-64	Physicist, Research Group, High Voltage Engineering Corp.

Publications

Thesis, "The Branching Ratios of Gamma Rays from Excited States of N^{14} and F^{20} "

"Space-Charge Expansion of a Positive Hydrogen Ion Beam Leaving a Duoplasmatron Ion Source"; A. B. Wittkower, A. Galejs, P. H. Rose, R. P. Bastide; Rev. Sci. Instr. 33, 515 (1962).

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Publications - continued

"Injection of Intense Neutral Beams into a Tandem Accelerator"; A. B. Wittkower, P. H. Rose, R. P. Bastide, N. B. Brooks; Rev. Sci. Instr. 35, 1 (1964).

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(In addition see papers co-authored with Rose et al.)

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Education

B. Sc., Physics, McMaster University, 1952

M. Sc., Physics, McMaster University, 1953

Ph. D., Physics, McMaster University, 1956

Professional Experience

1959-present	Ion Physics Corporation. The Particle Physics Department consists of four subgroups whose studies are directed toward radiation damage, environmental simulation, ion source/plasma physics, pulsed beam heating of materials, cathode development, radiation dosimetry, nuclear cross sections, micrometeoroid acceleration (electrostatic) and special accelerator applications.
1956-59	Convair Nuclear Laboratory. Senior Nuclear Engineer. Responsible for the development of (neutron and gamma ray) spectrometer systems for the USAF-ANP program. Also served on the Laboratory Safety Committee and conducted effluent monitoring and control, assay of contaminants in reactor cooling systems and high altitude monitoring of fission product activity.
1953-56	Hamilton Medical Research Institute. Research Assistant. Engaged in the application of the techniques of gamma ray spectroscopy to the field of biophysics-radioiodine uptake determinations and analysis of biological specimens for radioisotope content, etc.
1952-56	McMaster University. Graduate Student. High resolution beta and gamma ray spectroscopy and fast scintillation coincidence spectroscopy applied to the investigation of the complex decay schemes of some of the short-lived platinum group isotopes.
1952 Summer	National Research Council of Canada. Division of Radio and Electrical Engineering.

Publications and Patents

"Coincidence Studies of the Decay of In^{114}", Can. J. Phys. 32, 35 (1954).

"Disintegration of Ir^{192} and Ir^{194}", Phys. Rev. 96, 1599 (1954).

"The Decay of Rh^{186} and Rh^{188}", Can. J. Phys. 35, 69 (1956).

"The Neutron Induced Activities of Iridium and Osmium", Ph. D. Thesis, McMaster University (1956).

"The Decay of Os^{185}", Can. J. Phys. 35, 1159 (1957).

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"Energy Supply and Storage Considerations for a High Power Pulse System" (C), with P. R. Wiederhold and A. S. Denholm, Proc. IDA Pulse Power Conf., Vol. II (S), Washington, D. C. (February 1963).

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"Observations of Magnetically Self-Focusing Electron Streams", Appl. Phys. Letters 8, No. 1, 18 (1966).

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"Charge Storage Phenomena and Spontaneous Electrical Breakdown in Electron Irradiated Materials", with J. Dow, USAMC Conf. on Rad. Effects on Explosives, Picatinny Arsenal, Dover, New Jersey (May 1966).

DR. SAM V. NABLO (Continued)

"Studies of the Bennett Pinch in a Relativistic Electron Stream", with S. E. Graybill, Bull. Am. Phys. Soc. 11, Series 2, No. 1 (January 1966).

"High Potentials in Electron Irradiated Dielectrics", with B. Gross, Accepted for Publication, J. Appl. Phys. (1967).

Professional Affiliations

Senior Member, Electrical Propulsion Committee, American Institute of Aeronautics and Astronautics; American Physical Society; American Vacuum Society; Canadian Association of Physicists.

DR. A. S. DENHOLM (Continued)

"High Voltage Generation in Space: The Parametric Electrostatic Machine", with J. G. Trump and A. J. Gale, Progress in Astronautics and Rocketry, 3; "Energy Conversion for Space Power", Academic Press, New York, 745 (1961).

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"Energy Supply and Storage Considerations for a High Power Pulse System", with S. V. Nablo and P. R. Wiederhold, Pulse Power Conference, Washington, D. C. (February 1963).

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"High Voltage Technology", Invited Paper, First National Particle Accelerator Conference (March 1965); IEE Trans. on Nuclear Science, NS-12, No. 3 (June 1965).

Plus other papers, Government reports, and patents in the fields of electrostatics, high voltage and high vacuum technology.

Professional Affiliations

Senior Member, American Institute of Aeronautics and Astronautics; Associate Member, American Institute of Electrical and Electronic Engineers; Associate Member, Institution of Electrical Engineers (London); Past Member, AIAA Technical Committee on Electric Power Systems, and AIEE Technical Committee on Radio Interference (High Voltage).

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Education

B. Sc., Physics and Mathematics, National University of Ireland, 1956

Ph. D., Electrical Engineering, University of Liverpool, England, 1961

Professional Experience

1965-present — Ion Physics Corporation. Senior physicist and manager of program on high voltage breakdown in vacuum. Engaged in projects requiring the insulation of extra high voltage using solid, liquid and high pressure dielectrics, the switching of high powers and the generation of intense pulses of radiation.

1964-65 — Curtiss-Wright Corporation, Advanced Energy Conversion Group. Project Engineer. Engaged in the following projects: electrogas-dynamic high voltage generation; induced corona between charged clouds and grounded electrodes; electrical breakdown characteristics of mixtures of air and SF_6 under static and dynamic conditions; design of colloidal ion and gas jet ion generators.

1960-64 — Associated Electrical Industries, Ltd., Manchester, England. High Voltage Research Laboratory, Research Physicist. Directed the following projects: electrical breakdown characteristics of uniform and non-uniform field gaps in mixtures of air, CO_2, N_2 and SF_6 at pressures up to 20 atmospheres; investigation of the parameters that affect breakdown; flashover of insulators in oil, in vacuum and in compressed gases; the plasma-jet trigatron; point-plane corona discharge in air; condensation nuclei; test and development of high voltage components of electrical equipment; breakdown of liquid dielectrics.

1956-59 — University of Liverpool, England. Post Graduate Research Student. Investigation of electron removal processes in the after-glow of pulsed gaseous discharges in Ar, He, Ne, N_2, O_2 and mixtures thereof; attachment, diffusion, mobility, metastables.

Publications and Patents

"The Microwave Discharge", Ph. D. Thesis, University of Liverpool (1961).

"Electron Removal Processes in the Afterglows of Microwave Discharges in Ar and O_2", with M. C. Sexton and J. J. Lennon, Proc. Fourth International Conference on Ionization Phenomena, Uppsala (1959).

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"Measurement of Time Lags in SF_6", with G. Govinda Raju, Brit. J. A. P. (to be Published).

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Professional Affiliations

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