DEPARTMENT OF THE AIR FORCE
HEADQUARTERS 377TH AIR BASE WING (AFMC)
KIRTLAND AIR FORCE BASE, NEW MEXICO

18 MAY 2015

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Mr. John Greenewald
[redacted]

Dear Mr. Greenewald

In accordance with 5 U.S.C. § 552a, The Privacy Act, 5 U.S.C § 552, The Freedom of Information Act (FOIA), DoD Policy Memorandum 01-CORR-101, entitled "*Withholding of Personally Identifying Information Under the Freedom of Information Act*," and DoD 5400.7-R, your 25 July 2014 request for the document titled *Directed Energy Weapons Test Facility* has been partially exempted from release under 5 U.S.C § 552(b)(3) and (b)(6).

The requested document would include the release of information exempted from release under 5 U.S.C § 552(b)(3). This statute allows withholding information under the FOIA that is exempted from disclosure by other federal statutes. In this case, 10 U.S.C. § 130 authorizes the Secretary of Defense to withhold "technical data with military or space application in the possession of, or under the control of, the Department of Defense, if such data may not be exported lawfully outside the United States without an approval, authorization, or license under the Arms Export Control Act." The redacted portions contain technical information that is not releasable outside the Department of Defense. Furthermore, the redacted portions are controlled by export restrictions which cover sensitivities relating to current military data not authorized for release under the Arms Export Control Act.

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Accordingly, the requested document is released to you, with the exception of information which is exempt under the FOIA. If you wish to appeal this decision, you will need to write to the Secretary of the Air Force. Your letter must be received within 60 (sixty) calendar days from the date of this letter. Please include your reasons for reconsideration and attach a copy of this letter. Mail your appeal to the following address:

Secretary of the Air Force
Thru: 377 MSG/SCOK (FOIA Manager)
2051 Wyoming Blvd SE
Kirtland AFB, NM 87117

Sincerely

LANCE K. KAWANE, Colonel, USAF
Vice Commander

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Directed Energy Weapons Test Facility

ASD Technical Documentary Report No. ASD-TDR-63-29
AUGUST 1963 • AFSC Project No. 3805

DIRECTORATE OF ARMAMENT DEVELOPMENT

Det 4, AERONAUTICAL SYSTEMS DIVISION

AIR FORCE SYSTEMS COMMAND • UNITED STATES AIR FORCE

EGLIN AIR FORCE BASE, FLORIDA

(Prepared under Contract No. AF 08(635)-2795 by Ion Physics Corporation, Burlington, Mass, author A. S. Denholm)

GROUP-4
Downgraded at 3 year intervals;
Declassified after 12 years.

[redacted]

ASD-TDR-63-29 [redacted]

DETACHMENT 4
Directorate of Armament Development
AERONAUTICAL SYSTEMS DIVISION
Air Force Systems Command
UNITED STATES AIR FORCE
Eglin Air Force Base, Florida

REPLY TO
ATTN OF: ASQWR/[redacted]/67-3352

SUBJECT: Technical Information Concerning the Air Force Atomic Particle Beam Space Weapons Research Program

TO: Recipients of ASD-TDR-63-29

1. This technical report is one of the documents published under the subject program (AFSC Project 3805). This report is the result of theoretical and experimental investigation concerning the basic feasibility of particle beam accelerators operated as space weapons. This report is intended to provide you with the latest information concerning particle beam accelerator weapons concepts and related topics. Subsequent reports in the subject program will also be sent to your office if there is sufficient interest within your organization concerning advanced radiation space weapon systems concepts.

2. We would appreciate your bringing this report to the attention of any persons in your organization who might have an interest in the subject of radiation space weapons. If your office has no immediate use for this report please forward it to your technical library or return it to this Detachment. We would also appreciate your reviewing the distribution list of this report and informing this office of any suggested corrections or additions to the list in order to provide proper distribution of future reports. In addition, we invite any technical or editorial comments concerning this report, or requests for more information concerning the Atomic Particle Beam Space Weapons Research Program from members of your organization.

FOR THE DIRECTOR

[redacted]

Lt Col, USAF
Assistant Chief, Weapons Laboratory

[redacted]

NOTICE

This Final Report was prepared by Ion Physics Corporation under Air Force Contract AF08(635)-2795, "Directed Energy Weapons Test Facility". The work was administered under the direction of Weapons Laboratory (ASQWR) Detachment 4, ASD.

The studies began on May 1, 1962 and ended on December 31, 1962. Dr. A. S. Denholm was overall program manager with R. Britton acting as project engineer on that part of the studies concerned with the ultra high voltage facilities for the study of vacuum insulation. The studies required many talents. The major contributors were:

K. Arnold	A. J. Gale
R. Britton	I. Kohlberg
R. Cheever	S. V. Nablo
P. DeBeurs	P. Wiederhold
A. S. Denholm	J. Weisman

This report concludes work under the contract and is the only report. It is classified SECRET because of the data it contains related to directed energy weapons technology.

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ILLUSTRATIONS

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LIST OF MAJOR SYMBOLS

Symbol	Definition	Dimensions
N_p	ambient plasma density	cm^{-3}
N'_p	total plasma density	cm^{-3}
N_n	neutral density	cm^{-3}
V_b	projection (beam) velocity	cm/sec
ℓ	length of beam travel	cm
e_o	initial energy flux	$ergs/cm^2/sec$
e_m	measured energy flux	$ergs/cm^2/sec$
m_p	positive ion mass	g
b	distance of closest approach for coulomb interactions	cm
m_1	mass of incident particle	g
m_2	mass of target particle	g
m_o	reduced mass: $m_o = m_1 m_2/(m_1 + m_2)$	g
λ_o	DeBroglie Wavelength	cm
e	electronic charge	4.8×10^{-10} cm
a_o	Bohr Radius	5.29×10^{-9} cm
v	general notation for velocity	cm/sec
$\hbar$	Dirac's constant	1.05×10^{-27} g cm^2/sec
a_s	atomic screening distance ($a_s = a_o Z^{-1/3}$)	cm
p	impact parameter	cm

Symbol	Definition	Dimensions
ξ	ratio of distance of closest approach b, compared to the screening length, a_s, $\xi = b/a_s$	
v_o	"Bohr velocity" ; $v_o = e^2/\hbar$	2.3×10^8 cm/sec
E_b	kinetic energy of beam particle	ergs
w	collision probability	
ℓ_c	drift chamber length	cm
N_b	beam density	cm^{-3}
T_p	ambient plasma temperature	°K
h	Debye length	cm
ρ	mass density	$gram/cm^3$
c_h	specific heat	cal/gram
K	conductivity	cal/sec°K cm
T	temperature	°Kelvin
x	distance	
D	diffusivity	cm^2/sec
$\bar{\sigma}$ Pr	pressure	kg/cm^2
$\xi \rightarrow \xi_1$	displacement	cm
c	speed of light	cm/sec
c_s	speed of sound	cm/sec
G	shear modulus	kg/cm^2
E	Young modulus	kg/cm^2
c_ℓ	propagation velocity of longitudinal displacements	cm/sec
c_t	propagation velocity of transverse displacements	cm/sec
α	thermal expansion coefficient	cm/°K

Symbol	Definition	Dimensions
cal/ joules	mechanical heat equivalent 4.17	
μsec	microsecond = 1×10^{-6} sec	
b_1	average distance of the incoming particle from nucleus	
m_H	proton mass	kg
m_e	electron mass	kg
Δt	delivery time	sec
Z	atomic number	
β	$\frac{v}{c}$	
B	radiation conversion length or radiation length	cm
μ	linear absorption coefficient	
W_c	electron energy, where $\left(\frac{dW}{dx}\right)_{ion} = \left(\frac{dW}{dx}\right)_{rad}$	Mev
λ	wavelength	
ϵ_0	permittivity of vacuum 8.85×10^{-12}	F/m
μ_0	permeability of vacuum 1.25×10^{-6}	H/m

[redacted]

SUMMARY

The objective of the program described in this report was to evolve design plans and an evolutionary program for a high-vacuum test facility suitable for use in the Directed Energy Weapons Development Program. High vacuum is, of course, the environment of space.

Facilities for the development and testing of laser type weapons are different from those for particle beam weapons (ions, electrons), and this, together with the fact that a large laser testing facility is being developed elsewhere, led to a concentration on facilities for the particle beam weapon.

A major problem in the acceleration of particles to high energies, particularly using a single potential drop device, is the support of large potentials in the vacuum environment. It was hoped that a facility suitable for the development and testing of directed energy weapons components would be suitable also for the study of techniques for the support of very high voltages in space. Such a dual purpose facility was found to be conceivable, but not advisable. Consequently, the study proceeded along paths which are interrelated but separate. Progress along one path determined the facilities for the development of directed energy weapons, and along the other, facilities for solving the high voltage insulation problem.

A study of facility requirements was impossible without a close examination of the several directed energy weapons concepts. This showed the need for information on target damage and beam/environment interactions. Consequently, these areas were studied theoretically at some length, which confirmed the belief that adequate experimental data on target and environmental effects were needed to determine the utility of particle beam weapons.

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The development of a potential drop particle accelerator with adequate stored energy and with reversible polarity is the fastest and most economical approach to beams of ions or electrons of sufficient power density to produce the required target and environmental interaction data. It appears that a 'drift' tube 25 meters long would begin to supply useful information on environmental effects. This drift tube would be extended as experiments progress and the utility of the particle beam weapon is confirmed.

The realization of high power potential drop accelerators requires research and development in several areas which are discussed in the report. These areas include power supply, energy storage, ion and electron injection, and beam handling. A growth plan for facilities to solve beam production and acceleration problems is presented as part of an overall growth plan for particle beam weapons (Fig. 22).

A major part of a facility for the study of very high voltage effects in the space environment is the vacuum chamber inside which the studies are made. The voltages which are required inside this chamber dictate its dimensions. The standard method for obtaining high voltage inside a vacuum system is to generate outside and use a feedthrough bushing. It appears possible to extend this technique, which has been developed to above 1 MV at IPC, to about 5 MV. However, a more fruitful approach is to develop generators which can operate inside the chamber using vacuum for their external insulation. Generators of this form are almost directly applicable to the space borne accelerator.

The report concludes with a growth plan for high vacuum facilities which would permit the study of potentials up to 8 MV and develop the high voltage technology required for the operation of accelerators in space.

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1. INTRODUCTION

1.1 GENERAL

This study is related to Directed Energy Weapons concepts and consequently it is worthwhile discussing the present significance of the nomenclature. The title "Directed Energy" presumably was coined when the possibility of using electromagnetic radiation directly for target destruction was being considered. The main advantage of a weapons scheme based on a beam of radiation is in the fast target interception which is possible because of the velocity of propagation, which is the ultimate. Obviously, laser weapons fall directly in this category. Ion and electron beam approaches to a weapon are not strictly "Directed Energy" unless one assumes energy to include kinetic energy, in which case such mundane means of destruction as the gun and bullet could be termed a directed energy weapon system.

It is necessary then to define the term "Directed Energy" as applied to a weapon system, and it is suggested that the nomenclature be applied to a weapon system where the velocity of propagation is a significant fraction of the speed of light. It is a peculiarity of the several concepts that electrical forces are required in the penultimate stage of the weapon.

The various directed energy concepts will be discussed in some detail later, but it is worth introducing some of the ideas at this point. Possible approaches to a directed energy weapon include laser beams, plasma projection and electron or ion beams. Ion beams may be neutralised before projection to give an uncharged atomic or molecular beam. Laser beam weapons are attractive for focusing on a target but suffer from a very poor power efficiency and the fact that damage effects are superficial and are likely to cause only sublimation of material. Plasma projection concepts have so far been eliminated due to the difficulty in containing a dense plasma over useful projection distances.

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Ion or electron beam weapons appear the most feasible, but with the present state of the art are far removed from practicality. Programs such as the present one are aimed at closing this gap.

For obvious reasons, directed energy weapons are more feasible for operation in a very low pressure environment, and the altitude required for the operation of a directed energy concept is of more than passing interest. In considering the utility of any concept the most logical place to start would be in determining if it could significantly damage a target. Consequently, a considerable section of this report is devoted to target damage effects. Of comparable importance, and related to minimum altitude for operation, is the interaction of the directed energy with the environment. This has also been treated at some length, and the need for this will become clear from the program philosophy outlined below.

1.2 PURPOSE OF THE PROGRAM

The purpose of this program was to conceive test facilities for the development of directed energy weapons components, and hopefully, for the ultimate testing of a "prototype" weapon. To be realistic the ultimate facility for a complete weapon would not be built without the prior building and operation of smaller facilities for the proving and development of each of the component parts of a weapon. It was the aim of the program to produce a scheme for such a planned growth towards the ultimate facility, with indications of the timing and funding which would be involved.

Obviously the facilities could not be conceived without a close examination of the various approaches to a weapon and their weaknesses. The extent of the weaknesses then determine whether or not a particular approach is worthy of test facility considerations.

A further requirement of the facilities was that they be suitable for examining the electrical insulation strength of high vacuum at very high voltages. This was primarily to support a concept of electrostatic energy storage using

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the space environment as a dielectric which was proposed under another contract (AF08(635)-1636), but such studies of vacuum insulation are also desirable in support of high energy accelerators in space, even where the space environment is not the energy storage medium.

It was possible to conceive facilities which could serve both the components testing and the vacuum insulation tests but this was not considered a sound approach. The design of the dual purpose facility for reasonable dimensions requires the making of assumptions on vacuum voltage insulation at the higher potentials which may not be valid. If these assumptions proved to be incorrect, the facility could be of minor utility and, since the concept of a directed energy weapon is not necessarily tied to the support of megavolt potentials across vacuum gaps, the ultra high voltage vacuum insulation facility should be separate from the facility for examining other directed energy problem areas. In support of this two facility approach it should be noted that all present methods of accelerating charged particles to energies above about 1 MV use graded accelerator tubes.

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2. FACILITY FOR THE STUDY OF DIRECTED ENERGY WEAPONS CONCEPTS

2.1 CHOSEN WEAPON CONCEPT AND ITS JUSTIFICATION

The preliminary design of a facility useful for the study of the directed energy system must be based upon some initial, necessarily restrictive, assumptions concerning the nature of the projector itself. In order that this study could accomplish useful conclusions concerning not only the type of facility required, but evolve, as well, the philosophy of the experimental program which could be conducted with it, an early decision was made on the weapon system type that should be considered in this program. The considerations upon which this decision was based and the flexibility it permits will therefore be outlined.

Continuing studies at Ion Physics Corporation under AF08(635)-2166[1] and earlier efforts elsewhere[2,3,4] have provided considerable insight into the fundamental limitations of the various approaches to energy projection in the extraterrestrial environment. Of those techniques considered, the charged particle or electrostatic accelerator, the plasma projector and recently developed sources of coherent radiation (lasers) have received the greatest attention due to their relatively promising characteristics for the application. The tactical utility of each of these may be evaluated on the basis of five primary criteria, namely: divergence of the projected beam, energy efficiency of the weapon system, energy density at the plane of the projector, velocity of the directed beam and finally, mode of interaction at the target itself. Since the forementioned reports have treated these criteria, for all but the laser, to varying degrees, only a brief qualitative review of the significance of each to total system considerations will be discussed in turn below. The neutral particle system will be considered as synonymous with a charged particle projector as it is subject (at least within the projector itself), to the same limitations imposed by electrostatic acceleration techniques.

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The divergence angle α of the projected beam in the charged particle systems arises from repulsive coulomb forces within the beam itself as well as from the thermal motion or temperature of the accelerated particles. In addition, the effect of the ambient environment must also be considered in evaluating "divergence." Thus, the effects of scattering, charge-exchange and excitation during the drift phase must be determined in addition to the interaction of the beam with the ambient electric and magnetic fields. The former phenomena (coulomb, thermal) are much better understood at the present time[5] than are the latter, particularly for the relativistic regime of drift velocities. In view of this unbalance, considerable effort has been devoted to analysis of these latter effects with the charged particle system, and the results are presented in Section 2.6 under Drift Tube Considerations. A useful review of our knowledge of the divergence problem for the plasma system is presented in Ref. 6 and, along with the graphical results of Ref. 2, provide a useful introduction to the complexity of the divergence - range considerations so fundamental to weapons evaluation.

The energy efficiency η of the system is broadly defined as the ratio of the energy contained within the (useful cone and pulse length of the) projected beam to the total energy expended in generation of the "shot" pulse as well as in its focusing. This figure of merit is of prime importance in approaching the power supply problems implicit in the directed energy concept[7] due to the extreme energy storage requirements of even a high efficiency projector. All types of energy loss mechanisms must be considered, including those associated with the storage system itself. At the present time we can only make useful efficiency estimates for the projector per se while excluding the primary supply efficiency itself; i. e., for the energy storage system, electrical power source and pulse energy converter. This parameter is unquestionably the best defined, at present, of the five considered here in view of a reasonably exact knowledge of the state of the art of the various "sources" themselves coupled with those data relating to supply systems outlined elsewhere.[1,7]

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The energy density ξ of the beam at the plane of the projector itself provides a measure of the capability of the system provided that kill mechanisms and divergence are adequately understood for the device. If one could neglect the "post-acceleration" effects on beam divergence and the resulting decrement in energy density at the target, it would be useful to characterize the beam itself in terms of its directivity. For a beam of energy density ξ and divergence half-angle α, the beam directivity is expressed as $\xi/\pi\alpha^2$. (Amperes/cm^2/steradian where α is the beam half-angle at the cross-over or minimum beam radius.) If one can further define this beam radius "r" near the projector plane, then the directivity becomes $(J/\pi r^2)(1/\pi\alpha^2)$ or $J/\pi^2\epsilon^2$ where J is the beam energy and ϵ is the beam emittance; i.e., $r\alpha$. This parameter can then include both ξ and α in a restrictive sense.

The velocity v of the directed beam is a critical parameter as it constitutes the reason "why" for these directed energy studies. Tactical considerations of the effects of projection velocity are presented in Ref. 1 and 2 and indicate that for the intended application (space vehicles in Keplerian earth orbits) projector velocities of $> .1$ c are required for present tracking errors (0.5 milliradians). The lead angle required varies inversely as the projection velocity and is, of course, small for relativistic velocities for these "near-earth" trajectories. In addition, the beam velocity for charged particle systems is intimately connected to the divergence or expansion considerations during projection. In particular, for a given power density within the beam, the charge density and hence the radial electric field (as derived from a solution of Poisson's equation) will vary inversely as the velocity v. The self-focusing effects of relativistic beams are of interest here, particularly for electron streams, and the strength of this force produced by the azimuthal field as well as the radius of curvature of the particle in the ambient field, both vary directly as the particle velocity.

The mode of interaction of the beam at the target determines the kill mechanism and hence the tactical utility of the entire system. Implicit in

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considerations of the interaction mode are techniques of weapon countermeasures. Recent work conducted under this[2,6] (Directed Energy) and related programs[8] (ORION) has provided only scant information relating particularly to the effects of high energy, high density plasma impact on various materials, and has yielded a poor prognosis for the usefulness of the plasma system as a tactical weapon. There is a similar paucity of data[9] for the high density photon beam and the nature of its interaction at a solid surface, although several government supported programs are now directed to this area.[10] Rather more data are available relating to the interaction of high current density charged particle beams from high intensity accelerator studies, particularly with energetic beams.[11] Experiments designed specifically for the investigation of the metallurgy of damage mechanisms are still wanting in the energy region of interest to this program, and some definitive data in this area for "heavy" charged particles will hopefully be available in the near future.

In summary then, it is seen that of the five critical parameters considered here in the evaluation of the several weapon concepts, the least data are available for elucidation of the "kill" mechanism. However, with the information available, the high intensity charged particle beam would appear to be the most effective, based largely upon countermeasure considerations for the various systems. The main advantage of the high intensity photon source or optical maser obviously lies in its high directivity; however this advantage is much less obvious (as compared to the particle concept) for high power lasers as Sage[12] has pointed out. These limitations are yet to be fully demonstrated on large aperture lasers at useful power levels. Systems are under study elsewhere[10] for evaluation of these capabilities, and although partially communications oriented, will be readily useful for the purposes of this program.

The facility study outlined in this report therefore pursues considerations relating primarily to a charged particle linear acceleration system. Assuming that our present knowledge of the range of kill energy requirements is adequate, there would appear to be no engineering barriers to the development

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of a low energy (2 Mev) prototype system which constitutes the early basis of the facility. The critical areas of beam propagation and target interaction may then be studied in detail with this facility in order that data may be acquired at energy densities of interest to the program. The Mark I (2 Mev) facility therefore represents the first prototype terrestrial directed energy system which will be capable of providing the experimental data required for the evaluation and extrapolation of those parameters outlined above and, in particular, for the study of beam propagation in a simulated environment. The analytical considerations outlined in Sections 2.5 and 2.6 of this report provide a foundation for the experimental program proposed for this (Mk I) facility.

A summary of order of magnitude data relating to the criteria used in system evaluation is presented below and is intended to be indicative of the mid-1962 state of the art in this area for instruments that might realistically be considered for the directed energy application. References are included for each system. The "prognosis" for target interaction effects in each case is a best estimate based upon considerations of possible kill mechanisms at the propagation velocities and power densities achieved to date. Any comments concerning vulnerability to countermeasures for each system would be premature in view of our limited knowledge of these interaction mechanisms.

Projector Type and References	Divergence (α)	Power Eff. (η)	Power Density (ℓ)	Vel. (v)	Pulse Length	Interaction Effect
Ion Beam (2, 4, 7)	$< 10^{-2}$ r	> 50%	10^{5} w/cm^{2}	.2c	10^{-3} s	good-excellent
Electron Beam (11, 13)	$< 10^{-3}$ r	> 95%	10^{7} w/cm^{2}	~ c	10^{-6} s	excellent
Optical Maser (13, 14)	$\sim 10^{-5}$ r	~1%	10^{6} w/cm^{2}	c	10^{-6} s	good
Plasma (2, 6, 15)	$> 10^{-2}$ r	< 40%	Low	.0005c	10^{-3} s	poor

[redacted]

The <u>energy density</u> of the beam at the beam crossover near the plane of the projector is a commonly used criterion. For our purposes, the product of the energy density and beam velocity constitute a more useful parameter, namely the energy flux or <u>power density</u> ξ of the beam, stated in watts/cm^2. Since the concept of beam directivity[16] as used in optics, is pertinent to this problem, it is useful to consider the equivalent beam <u>power directivity</u> δ expressed as $\xi/\pi\alpha^2$, where α is the half angle of the beam measured at the minimum beam diameter or crossover point. The units of δ are then watts/cm^2/steradian and are largely of use in injector-accelerator evaluation but ignore the critical problems of subsequent power loss during the drift phase. Since target interaction effects are rate dependent, it is felt that the use of power density should be adopted rather than the usual energy/unit area as the pulse period is implicit in ξ. The importance of pulse period τ is largely understood on the basis of energy dissipation considerations. It has been generally concluded that τ must be short (preferably less than 1 msec) in order that bulk thermal conductivity considerations no longer plan an important role (Section 2.5.2.3).

2.2 FACILITIES AND MAJOR PROBLEM AREAS

The previous section has indicated that the most promising approach to a directed energy weapon lies in the acceleration of ion or electron beams. (b) (3) (A) [redacted], [redacted]. The actual energy and energy density at a target which would be required will depend upon the results of experiments on the interaction of beams with the space environment and on target damage which will be made in the early stages of the proposed facilities.

(b) (3) (A) [redacted]

[redacted] (b)(3)(A)

The information on Table I is for direct potential drop machines which appear to be the best approach to high positive or negative beam currents for pulse durations up to 1 millisecond. Several forms of high voltage generator are available for the accelerator, and those which are worth considering are the Dynamatron, Cockcroft Walton, Van de Graaff and Insulated Core Transformer (ICT). The Dynamatron, Cockcroft Walton and ICT are limited to potentials of 3 - 4 Mev at the present time, but can produce currents 10 to 100 times greater than the Van de Graaff, which has a maximum output of about 1 milliampere. Both the Dynamatron, Cockcroft Walton and the ICT could be made for higher voltages, but largely because of the increasing dimensions the power generation becomes less efficient. Because the requirement for a pulsed accelerator is stored energy rather than high continuous current, the Van de Graaff is the best form of generator provided it has sufficient current capacity to supply any leakage associated with the stored energy. Van de Graaff designs exist for potentials up to 15 Mev and such accelerators are at present under construction. The current capacity of 1 ma should be quite adequate to supply the energy storage system (see Table I).

The acceleration of an electron beam is a more tractable problem than the acceleration of an ion beam, and unless otherwise stated the more difficult problem; i.e., the ion beam accelerator, is being pursued. Two approaches to the accelerator are shown on Figs. 1, 2 and 3. The advantages of the charge exchange machine (Fig. 3) lie in the ion source being at ground potential rather than in the terminal because the operation of a high current source

Table 1

Outline Parameters: Proposed High Pulse Current Accelerators

			See Note Number
Terminal potential (MV)	2	10	
Maximum pulse duration (sec)	10^{-3}	10^{-3}	1
Maximum terminal drop (kv)	100	100	2
Beam current for 10^{-3} sec pulse (amp)	1	1	3
Beam current for 10^{-5} sec pulse (amp)	100	100	4
Maximum charge flow (coulomb)	10^{-3}	10^{-3}	
Maximum energy in pulse (joules	$\sim 2.10^{3}$	$\sim 10^{4}$	
Energy density on 1 cm^2 (j/m^2)	2.10^{7}	10^{8}	5
Terminal capacitance needed($\mu\mu f$)	10^{4}	10^{4}	6
Stored energy in system (joules)	2.10^{4}	5.10^{5}	7
Time to charge from zero potential (sec)	20	100	8
Current drain due to leakage (μa)	2	10	9
Volume of capacitors (m^3)	0.22	5.5	10

Notes to Table 1

1. This is ample duration from both considerations of target damage and the holding of a typical high velocity target without continuous tracking during firing.

2. The operation of pulsed accelerators at HVEC suggests that a 100 kv drop with a 2 Mev machine is quite acceptable. Information on the allowable drop will be obtained from the first stage program. It is likely that greater than 100 kv drops will be allowable with the 10 Mev accelerator, and if so, this can be used to increase the beam current x pulse duration where desired. The allowable drop becomes much less where magnetic deflection follows acceleration. Approaches to reducing terminal drop are discussed in Section 2. 3. 2.

3. For positive ion operation.

4. For electron operation.

5. Focussing to spot sizes less than 1 cm^2 will be possible.

6. The terminal capacitance of Van de Graaff machines is usually 100 - 200 $\mu\mu f$.

7. The energy stored in Van de Graaff type machine is usually: 2 Mev ~250 joules, 10 Mev ~ 6250 joules.

8. Based on 1 ma charging current being available. Somewhat less may be available for the 2 Mev machine, but this will not be significant.

9. Based on meg ohm x μf product of 10^4.

10. Based on energy densities of 1. 5 j/in^3. Densities as high as 2 j/in^3 are available. For an essentially DC application higher densities may be possible since capacitor life and voltage stress is closely related to voltage reversals. However, initial outline design using 200 kv commercially available units as modules give larger volumes than Table 1 but the dimensions are still practical. Smaller module voltages will give better energy densities.

Table 2

Outline Parameters: Present High Pulse Current Accelerators

Location	Accelerator	Potential Energy	Peak Current	Pulse Duration	Pulse Energy	Tube Length
Rensselaer P. I. (N. Y.)	Linac (electron)	77 Mev	800 ma	4.5μs	280 j	8.2 M
Yale	Linac (electron)	60 Mev	700 ma	4.5μs	190 j	7.5 M
Livermore (Astron Project)	Pulse Transformer (electron injector)	1.7 Mev	150 a	0.25μs	64 j	--
Livermore	Injector (proton)	100 kev	2 a	1 ms*	200 j	--
Berkeley	C. W. Injector (proton)	370 kev	120 ma	1 ms	45 j	--

* Source provides pulse duration to 25 ms., but durations above 1 ms. not considered of interest here. Beam diameter was 4" and beam divergence about 10°.

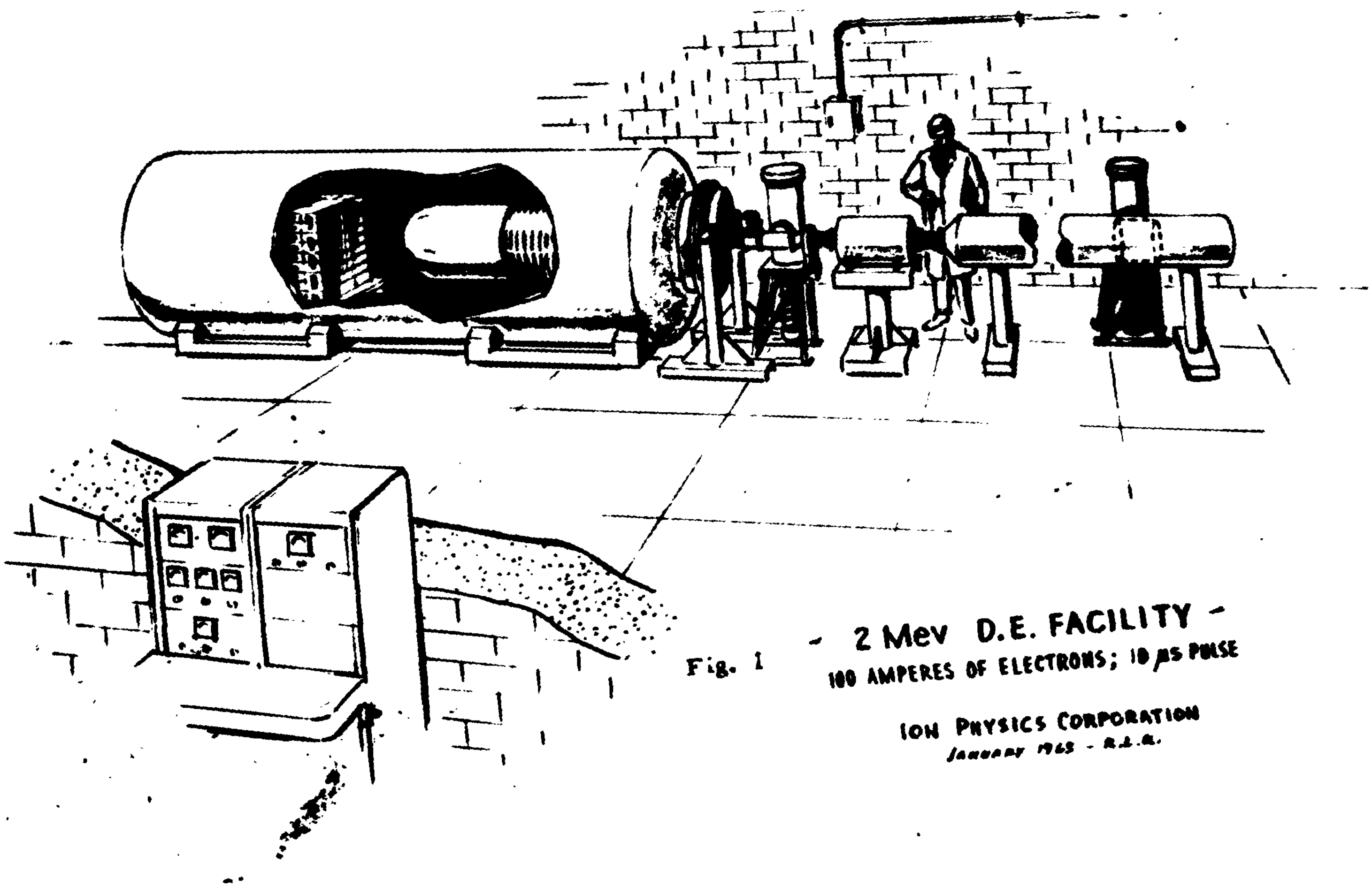

- 2 Mev D.E. FACILITY -
100 AMPERES OF ELECTRONS; 10 μs PULSE
ION PHYSICS CORPORATION

Fig. 1

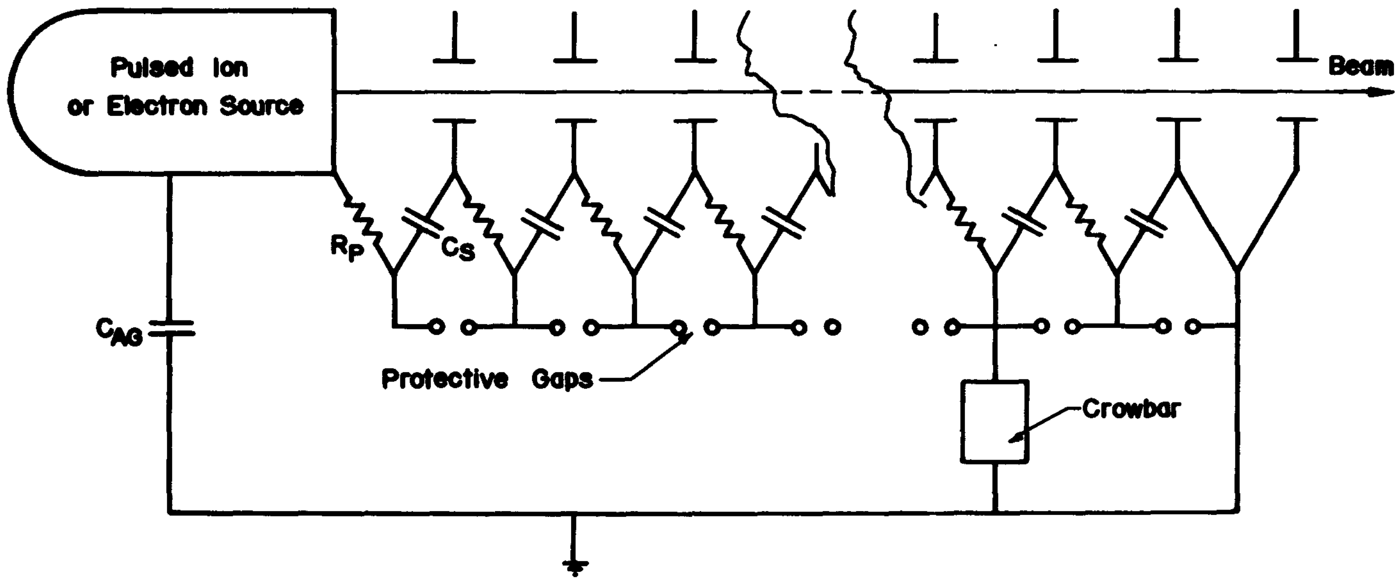


Fig. 2 Circuit Outline – Simple Potential Drop Accelerator

C_{AG} Energy Storage Capacitance
C_S Beam Stiffening Capacitance
R_P Protective Resistors

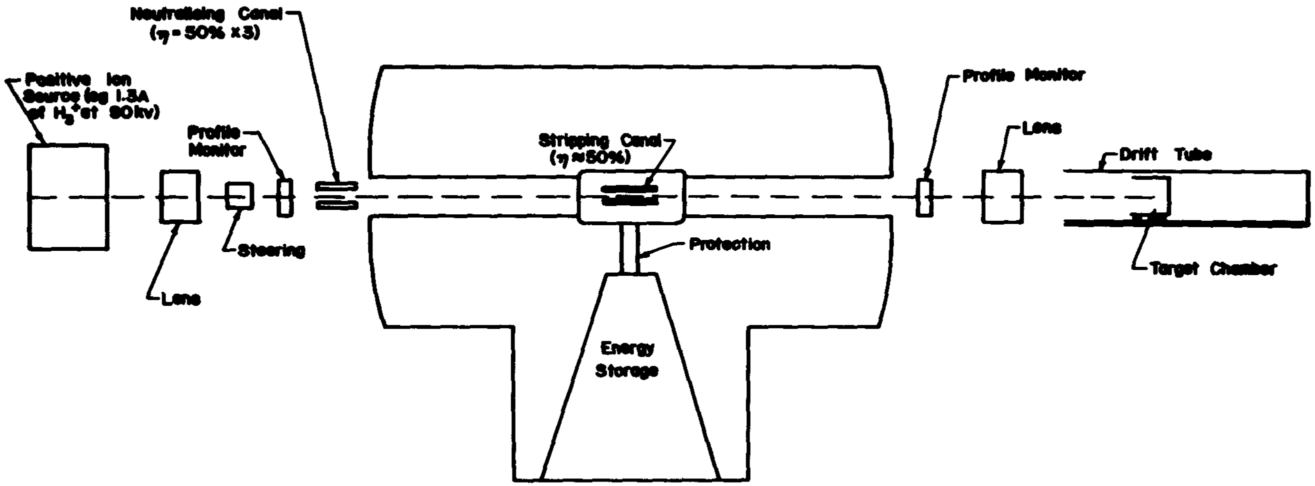


Fig. 3 Neutral Particle Injection Accelerator

in a terminal may lead to thermal problems and large pumping speed requirements down the accelerator tube. Starting with a 1.3 ampere source of H_3^+ (Fig. 3) which is believed attainable within the next two years, a one ampere beam output should be possible. In the neutralizing canal the H_3^+ dissociates to 3 of H, each of which are injected as neutral particles with a 50% efficiency so that the neutral 'current' to the terminal is about 2 amperes. In the terminal, conversion to positive ions is about 50% efficient, so that a 1 ampere beam is then accelerated to ground through the terminal potential.

However, the system of Figs. 1 and 2 is obviously a simpler concept and is preferred at the present time. The fact that only a pulsed beam is required means that the source can be operated on a gas pulse basis, possibly with pumping in the terminal, to alleviate the problem of pumping down the tube. Thermal problems in the terminal are also reduced because the source has to operate only in a pulsed mode.

The major problem areas in the accelerator concept are:

1) The ion source. This is treated together with the problem of injection into the accelerator tube in Section 2.4.1.
2) Power supply, energy storage and beam coupling (tube problems). This is treated in Section 2.3. .
3) Beam handling. This is treated in Section 2.4.2.
4) Drift tube. This component is needed to investigate the interaction of the beam with the space environment. Section 2.6 shows that significant data on this can be obtained with a ground based system of reasonable dimensions.

2.3 POWER SUPPLY AND ENERGY STORAGE

2.3.1 General

In this section consideration will be given to the power supplies and energy stores, both for the high powered accelerators which are proposed for target damage and environmental interaction studies and for the ultimate directed energy weapon which is assumed to be a potential drop machine. The power supply and possible energy store for the ultimate weapon require consideration since that system will require a test facility as the weapon is developed.

[redacted]

2.3.2 Facility Power Supply and Energy Store

The parameters of the accelerators which are outlined in Table I were determined both by the need for a certain range of energy densities on a target over a useful area and by a reasonable extension of present technology. The potential drop accelerator can operate either with a steady applied voltage or with an impulse voltage. The former has been chosen because it is simpler, gives better beam control and there is much greater familiarity with the technique. However, in the ultimate weapon an impulse voltage machine using, for example the Marx circuit if adequate energy can be stored capacitively, might be used since the superior total voltage insulation strength obtained with impulse rather than direct voltage is attractive. The most powerful high voltage impulse generators which have been made are probably 7.5 MV, 180 KJ at General Electric Company, Pittsfield and 8.2 MV 420 KJ at the Khar'kov Electrotechnical Institute (USSR).[17]

In the test facility the power supply problem is essentially one of voltage conversion to the high potential required by the accelerator. Apart from the ability to produce high potentials, the voltage conversion device has to be capable of supplying sufficient current to store the required energy in a reasonable time and to supply the leakage associated primarily with the energy store.

In deciding on the power conversion device those approaches capable of developing significantly greater than 1 MV DC were considered. Machines of interest were the Van de Graaff (belt machine), variable capacitance generator, variable reluctance generator, insulated core transformer, Cockroft Walton multiplier and the Dynamatron. All of these machines except the last are produced or are being examined experimentally in the HVEC group of companies (see Refs. 18, 19). The Dynamatron, which is an r.f. coupled DC supply[20] has been produced up to 3 Mev. The belt charging machine was chosen for the following reasons:

[redacted]

- It supplies adequate current (>1 ma).
- It is the simplest and cheapest approach.
- It has developed potentials approximately three times higher than any of the other machines, and is capable of further extension.
- It has been amply proven.
- Polarity can be reversed by simple switching.
- It is adaptable to space operation.

The accelerator shown on Fig. 1 uses a Van de Graaff supply and has dimensions corresponding to a 3 Mev machine which can accommodate a large beam tube.

None of the voltage supplies mentioned above could possibly supply the instantaneous power delivered in the accelerator beam, thus an energy store is required. This store is armed over a relatively long period compared with the delivery time of the beam and consequently the power from the supply can be fairly small. The instantaneous beam power with the 2 Mev accelerator is 200 Mw in the electron pulse, whereas the power available in the Van de Graaff is only 2 kw.

The stored energy needed by the accelerator is determined by the allowable terminal droop during the delivery of the beam and the charge in the pulse ($\Delta Q = C \Delta V$). The terminal drop in potential must be limited because it influences beam containment and focussing. Any post acceleration beam bending using magnetic fields would be very sensitive to terminal droop because of the variation in particle momentum, and it is because of this that a horisontal machine is proposed with both target chamber and drift chamber in line. The allowable droop will be the subject of early experiment in the facility, but experience with pulsed accelerators at HVEC indicates the drop in potential should be limited to 100 kv in a 2 Mev machine. A larger drop would probably be allowable at 10 Mev, but 100 kv has also been used in that design outline because it is desired to leave a margin for larger beam charges.

The drop of 100 kv and the beam charge of 10^{-3} C indicates that a terminal capacitance of 10,000 $\mu\mu f$ is required. It is necessary to ensure that the dimensions of this capacitance bank are not excessive and that the leakage current is tolerable. The dimensions of capacitors for various applications can be determined from allowable energy densities which are related to the particular application. The energy density of a given capacitor is proportional to the square of the voltage at which it is operated, and this voltage has a maximum value related to the lifetime desired, the number of voltage reversals and their severity. Figures 4a and 4b show typical relationships. The bank in this case will not experience voltage reversals except in the case of breakdown. Energy densities as high as 2 j/inch^3 are obtainable in an optimum package (e.g., optimum capacitance and voltage value). At the high voltage ratings and low capacitance ratings desired here the energy density is rather poor. However, the dimensions of a 10,000 $\mu\mu f$ 2 Mev bank based on a 50 kv, 0.1 μf capacitor is indicated on Fig. 1 where it can be seen that the bank is reasonably compact. The energy density of this 0.1 μf unit is 0.5 j/inch^3. It is interesting to compare this with the maximum energy density obtainable in a high dielectric strength material such as mylar, which is about 50 j/inch^3.

The leakage current in the bank is determined by the meg ohm xμf product, which is a measure of the quality of a capacitor. A value of meg ohm x μf = 10^4 is typical of a good unit, which gives a leakage current of 2 - amperes for the 2 MV storage bank, and 10 μ amperes for the 10 MV bank. The voltage across the capacitors in the bank has to be controlled by resistance grading, and this will give an added leakage current of perhaps 40 μ amperes and 200 μ amperes respectively. Other losses such as that due to corona will have to be limited by good high voltage design inside the pressure tank.

The energies in the 2 MV and 10 MV store are respectively 2 x 10^4 and 5 x 10^5 joules, which can be compared with energies of 250 joules and 6250 joules in typical accelerators. Obviously some thought has to be given to the possibility of breakdown in the system and the effect of these large energies

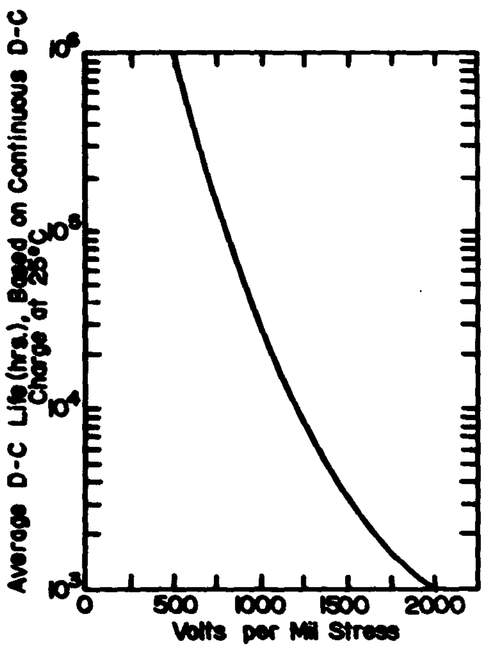


Fig. 4a Life-Stress Relationship for Typical Capacitor Material (Based on 5th Power Law)

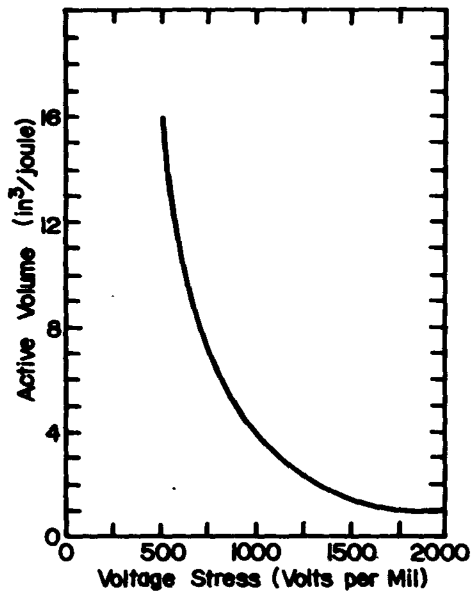


Fig. 4b Energy Density-Stress Relationship for Typical Capacitor Material

being dumped. Breakdown could take place either in the high pressure gas environment or through the vacuum of the accelerator tube. Even though the stored energy is of the order needed for the electrohydraulic forming of metals, discharge in the high pressure gas is not expected to cause serious difficulties, although this should be confirmed by experiment. With regard to breakdown in the accelerator tube, which is more likely, it is possible that the discharge current would be limited by space charge effects. Experiments at HVEC [21] where high pulsed currents from a vacuum arc source (~ 4 amperes of electrons) were accelerated to about 2 Mev showed that the maximum current was limited to about 1 ampere per cm^2 of tube area per MV/m tube gradient. This conflicts with experiments by Brasch and Lange[22] who obtained 1000 amperes through an accelerator tube using a 2.4 MV impulse generator, apparently somewhat to the detriment of the accelerator tube. In these last experiments, which were with a rather unusual tube, the current was 5 amperes per cm^2 per MV/m. Again, the effect of stored energy on accelerator tube breakdown should be the subject of experiment. The current limit mentioned above might apply equally well to the controlled discharge of the beam, and for 100 amperes of electrons the inside diameter of the tube should be at least 4 inches.

In considering protection against dumping excessive energy (current) at breakdown the first step is to increase the output impedance of the bank by adding a resistance between capacitor and terminal. This has two effects. It limits the discharge current and increases the discharge time, which allows the dumping of most of the bank energy via another path, for example a crowbar circuit. Unfortunately this resistance is limited by the allowable potential drop across it when the accelerator operates, and in the case of the 100 ampere pulse a maximum value would be about 500 Ω This gives a bank discharge time constant of 5 μ sec; which would require a fast acting crowbar to divert the discharge (if this were found to be necessary). Spark gap crowbar circuits have been developed for clearing transmitting tubes up to 350 kv, within 2 μs [23] and these tubes in some sespects are quite similar to accelerator tubes. These crowbars operate at atmospheric pressure, and a crowbar to operate within the accelerator tank at high pressure could be a much faster device since breakdown at high pressure develops much more rapidly than at atmospheric pressure.

The uncertainties associated with the operation of an accelerator with large amounts of stored energy suggests that the terminal capacitance should be increased in stages to 10,000 μμf during the experimental stage, perhaps in steps of 1000 μμf.

Another aspect of energy storage and particle acceleration is that of beam stiffening. The term 'stiffening' refers to the maintenance of accelerator tube gradient in spite of interactions of the beam with the tube. A loss of tube gradient can be by two causes.

The first is due to the movement of beam charge down the tube which causes induced charge flow in the accelerator column and loss of gradient, particularly at the source end of the tube. These induced charges flow in the stray capacitances between the electrodes of the accelerator tubes as well as in the storage bank while the front of the beam passes down the tube, but once the charge in the tube (beam) reaches equilibrium, there is no further net flow of charge in these stray capacitances by induction. The stray capacitance between sections on a 3 Mev Van de Graaff was measured and found to be approximately 250 μμf, and with this value the loss of gradient due to induced charge flow was found to be unimportant (see Appendix II).

The second cause of loss of tube gradient is actual interception of part of the beam by the electrode system, and this loss increases as long as the pulse lasts and beam is intercepted. The greatest stiffness is obtained by coupling the energy storage bank to each electrode as shown on Fig. 5, which would give 0.4 μf between electrodes. However, this constricts design and complicates protection, and the best approach is to increase the inter-electrode capacitance to an adequate value while retaining most of the stored energy in a separate bank. Typically the gradient on the accelerator tube

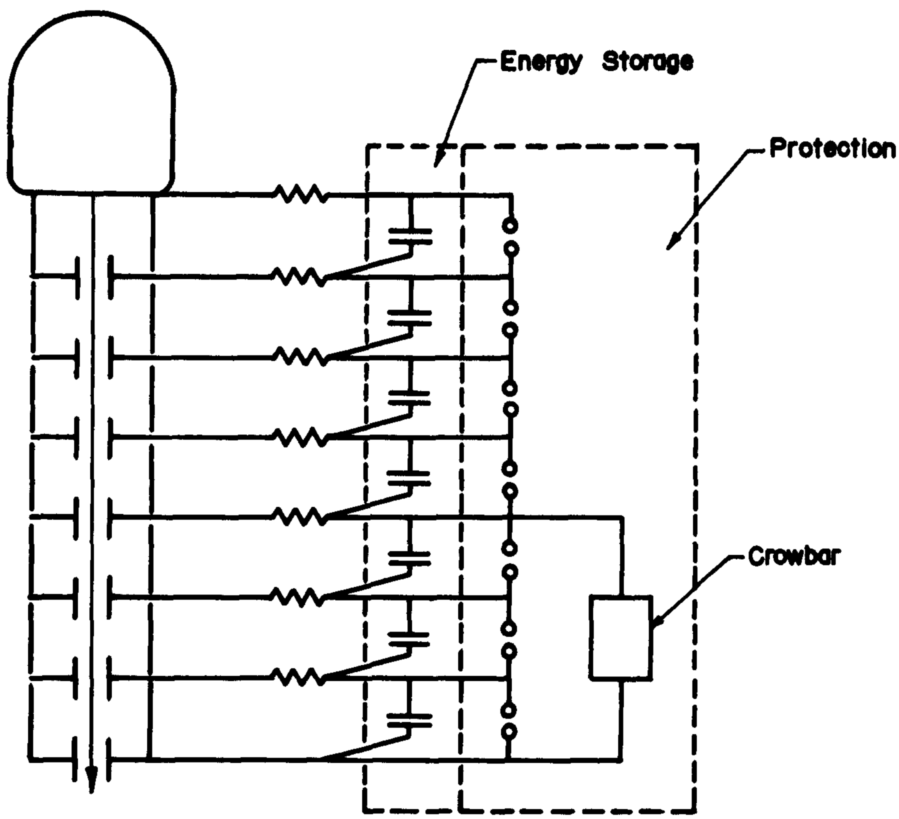


Fig. 5 Accelerator Coupled for Maximum Beam Stiffness

would be 50 kv per electrode section, and if 1% of the 100 ampere electron beam was intercepted by the first electrode, an interelectrode capacitance of 1000 μμf would give a potential drop of 10 kv in the first electrode section by the end of the pulse. Beam interception will have to be a subject for experiment, with initial experiments using tubes over-designed with regard to stiffness.

In conclusion some comments will be made on the maintenance of beam potential, still using terminal capacitance but with more sophisticated techniques.

In some instances, liners have been provided in accelerator tanks to reduce the variation in beam potential during delivery.[24] The liner is pulsed during the beam firing and the potential variation is impressed on the terminal of the accelerator through the stray capacitance to compensate the droop. This approach can be used using the energy storage bank for coupling as shown in Fig. 6a. The low voltage bank is charged to reverse potential through a high resistance before beam firing. When the beam pulse starts, switch s is closed (spark gap) and the linear fall in potential of the H. V. bank is largely compensated by the swing in voltage of the low voltage bank. Figure 6b shows the voltage variations. This technique could be applied eventually to the proposed accelerator systems either to increase their current capability or to decrease the variation in beam potential for a given current.

An interesting approach to the exact maintenance of beam potential which was proposed by R. J. Van de Graaff [25] is shown on a 2 Mev beam machine on Fig. 7. The charge which flows from the 2 Mev terminal in the primary beam is exactly compensated by a flow of charge in a beam between the 2 and 4 Mev terminals. In other words, the charge on the 2 Mev terminal remains constant so that there is no change in the 2 Mev beam potential during the pulse. An electron beam is easier to produce and handle than an ion beam, so that if the primary beam consists of electrons, a compensating electron

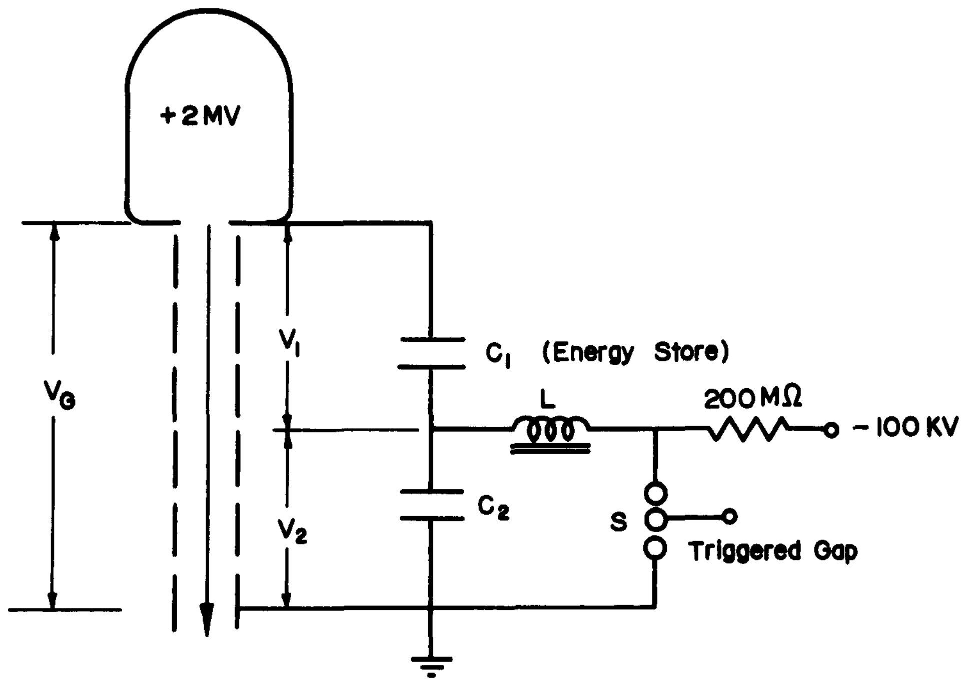


Fig 6a Driven Terminal Concept for Maintenance of Beam Energy During Discharge

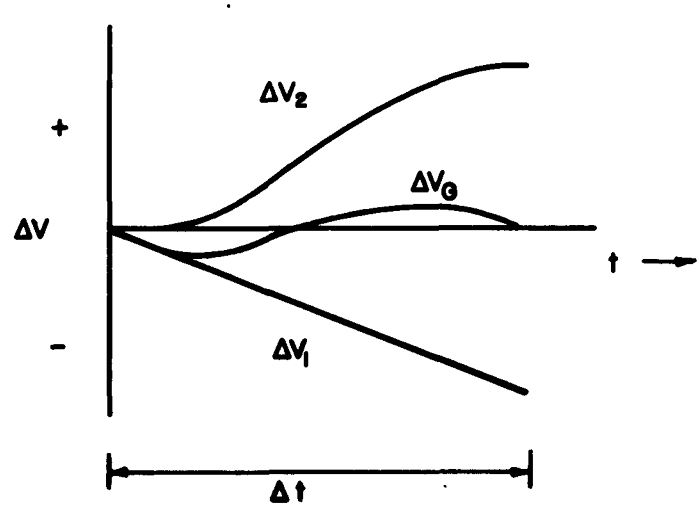


Fig. 6b Voltage Relationships with Resonant Pulsing of Terminal ($C_2 \gg C_1$)

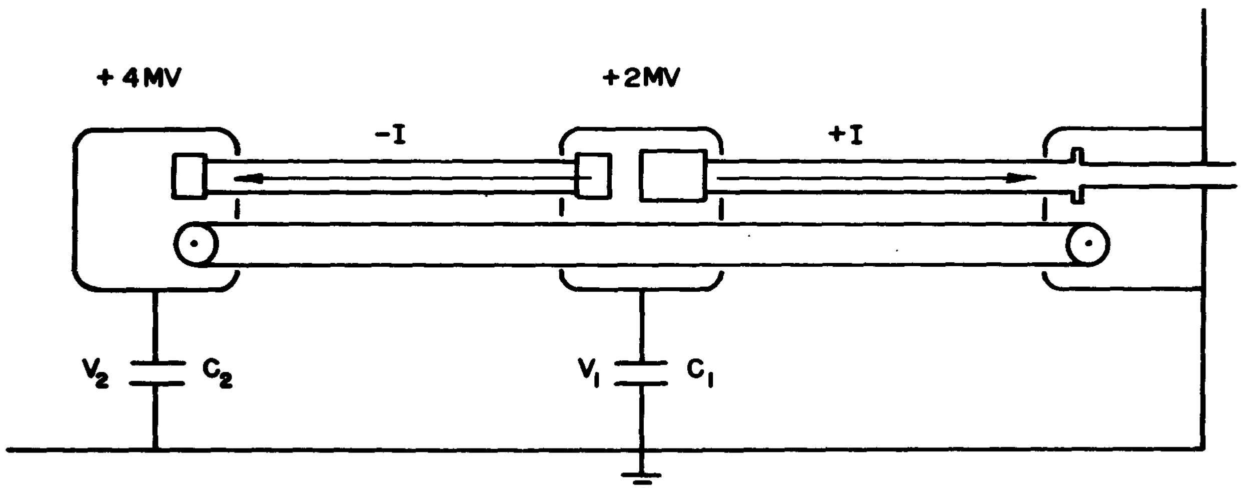


Fig. 7 Maintenance of Beam Energy using an Auxiliary Beam and 2 Terminals.

[redacted]

beam flows from the 4 MV to the 2 MV terminal, and if the primary beam consists of ions, a compensating electron beam flows from the 2 MV to the 4 MV terminal. Simple analysis shows that without any degradation in beam potential the following relationship holds:

$$\frac{\text{maximum useful beam energy delivered}}{\text{energy stored in higher voltage terminal}} = \frac{2\,(k-1)}{k^2}$$

where k is the ratio of the potential of the upper terminal to the lower terminal. For example, in the 4, 2 MV concept, about half of the energy stored at 4 MV could be delivered as useful beam without any degradation of potential. This concept may be important to the directed energy weapons program because a large part of the stored energy can be used in a mono energetic beam.

2.3.3 Application of Facilities to the Development of Energy Storage for Weapons

General It is visualized that the D. E. Test Facility will be utilized for investigations on large energy storage systems and their coupling to accelerators. High voltage vacuum breakdown studies are being conducted with the objective of holding multi-million volt potentials across vacuum gaps. If voltages in the order of 10^7 - 10^8 volts can be insulated in vacuum, energy storage can be obtained in sufficiently high densities by means of electric fields in vacuum. This is a major objective of the studies and test facilities described in Section 3.

Based on presently available data on vacuum breakdown, a solid dielectric capacitor bank would offer a better, but still far from ideal solution. Using the best available dielectric materials and assuming that they will support 10^6 volts/cm for extended periods of time in a space environment, such a system would have a volume of about 2000 m^3 for storage of 10^8 joules. Investigations of dielectric breakdown and solid dielectric capacitors in the vacuum (space) environment could be performed in the high voltage vacuum breakdown facility (Section 3). However, this concept is not very attractive and is not presently being pursued. A better, but certainly more complicated method, is the storage of energy in high magnetic fields.

[redacted]

Inductive Energy Storage Large quantities of energy can be stored inductively in magnet coils generating a high magnetic field. The energy density is given by:

$$W = \frac{B^2}{2\mu} \text{ joules/m}^3$$

with B in Webers/m^2

$\mu = 4\pi \times 10^{-7}$

A field of 15.7 Webers/m^2 = 157 kilogauss would represent an energy density of 10^8 joule/m^3. Because of the high ohmic losses in conventional magnet coils, the power required to keep the energy in storage would be prohibitive. Therefore, this concept would only be feasible if superconducting coils are used. But even taking into account the volume of the coil and the required helium liquefier with associated cryogenic equipment, energy densities two to three orders of magnitude higher than in capacitor banks may be possible.

The highest fields that have been generated in superconducting coils to date are about 70 kilogauss. Materials with critical fields in excess of 100 kilogauss have already been reported[26] although these materials are presently not suitable for large magnet coils. Recent developments [26,27] indicate that superconducting coils generating more than 100 kilogauss can probably be built in the not too distant future.

One concept of an inductive energy storage system with which it is possible to develop relatively high voltages, is shown schematically in Fig. 8. With switches S_2 and S_3 open and S_1 closed, the storage coil is charged up to a certain current level. The charging time depends on the DC generator and the time constant of circuit 1. When the coil is charged, S_2 is closed and S_1 opened. The energy is now kept in storage by the persistent current in circuit 2 (S_2 is a superconducting switch). Since there is no resistance in circuit 2, there are no energy losses. S_3 can now be closed and energy discharge takes place through the load when S_2 is opened.

It is quite possible that the best approach to the DC generator in this circuit would be an electromagnetic machine - also super conducting.

Many problems remain to be solved before the feasibility and applicability of this concept to D. E. Weapons is demonstrated. Some of these problems are:

- Design of very large superconducting coils generating high magnetic fields at high current densities.
- Development of a high voltage, fast-acting superconducting switch (S_2 in Fig. 8).
- Design of support structures to contain the large mechanical forces generated in the coil.
- Obtaining sufficiently fast discharge times while maintaining the storage coil in the superconducting state.
- Investigation of matching output impedances and coupling of the storage system to, for example, an accelerator tube.
- Protective circuitry to protect the equipment and dispose of the stored energy in case the coil goes normal in an uncontrollable manner.
- Coil and system protection against high voltages generated during discharge.
- Development of cryogenic systems and a helium liquefying plant to operate the system unattended in a space environment.

These problems are of considerable magnitude and some of them are currently under investigation as part of Contract AF08(635)-2166. This program is presently in an early state of development, but some comments with respect to the D. E. Test Facility can be made.

<u>Utility of the Proposed Facilities to Energy Storage Studies</u> The most promising approach to a D. E. Weapon involves the acceleration of charged particles to high potentials. However, high voltage limitations of the coil and switch in the concept of Fig. 8 would prevent the use of a single coil system and necessitate a bank structure similar to a capacitor bank. In its most elementary form, the accelerator tube with inductive energy storage might be as shown in Fig. 9. The inductive storage system is a current

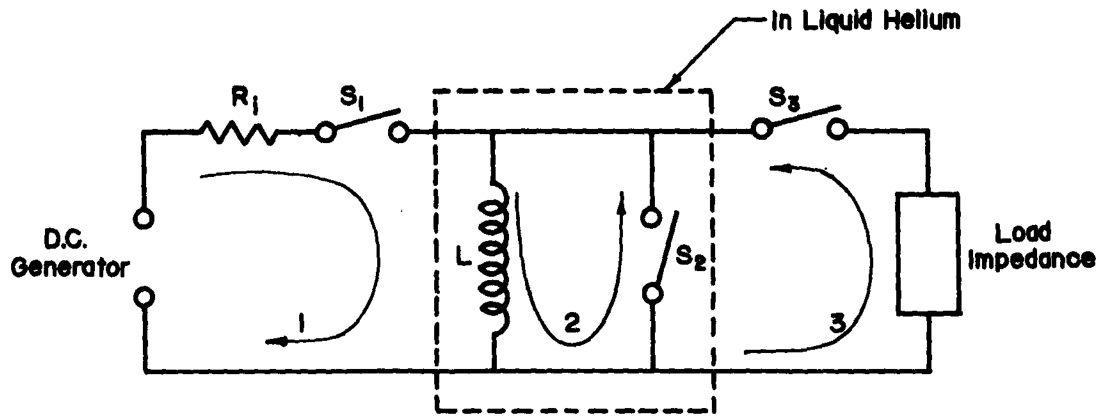


Fig. 8 Superconducting Inductive Energy Storage System

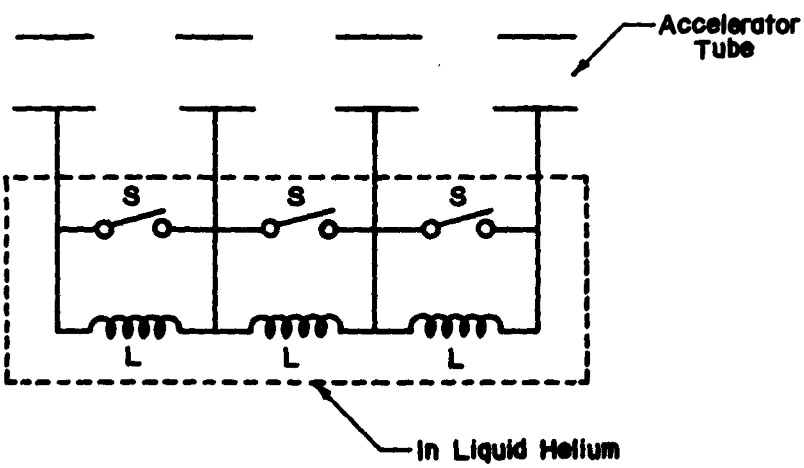


Fig. 9 Coupling of Inductive Energy Storage System to Accelerator Tube

[redacted]

device as opposed to a capacitor bank which is a voltage device. Consequently, the discharge voltage is highly sensitive to the load impedance and operation of the discharge switches must be properly synchronized. Parallel capacitors may be needed across the discharge switches to provide a sufficiently long rise time of the discharge voltage to prevent the coil from going normal during discharge and also to provide the desired pulse width.

After preliminary studies on smaller systems, it is visualized that these experiments can be continued by substituting a properly designed inductive system for the capacitor bank of the D. E. Components Test Facility. The coils and discharge switches require a liquid helium environment and are mounted in a suitable dewar system filled with liquid helium. For these experiments, the storage system need not be positioned in a vacuum chamber. Breakdown studies and the development of dewars, helium liquefying plant and cryogenic recirculating systems for unattended operation in space would benefit from the availability of the high voltage vacuum breakdown test facility.

The size of the cryogenic energy storage system, its cooling requirements and the time required to develop this system is difficult to predict and depends on the solution of the problems outlined above. Present efforts are on storage coils made with Nb Zr wire with a critical magnetic field of 70 kilogauss. Future availability and subsequent use of more sophisticated materials with higher critical fields is anticipated but depends on progress made in materials development. Development of the cryogenic switch is likely to be one of the most difficult and time consuming problems, but preliminary experiments can probably be performed using a conventional switch by eliminating the persistent current mode of operation in Fig. 8 and switching from charge to discharge operation directly. Assuming a sufficient effort put into the inductive energy storage investigations and satisfactory progress towards the solution of the problems outlined above, the feasibility studies and experiments may be completed in 1 to 1 1/2 years (1964). Completion of design and development of a prototype energy storage system for operation in conjunction

[redacted]

[redacted]

with the D. E. Components Test Facility may require another two (2) years (1966). Parallel with this last effort, a program should be conducted to study and develop a prototype space cryogenic system including helium liquefier, dewar, transfer and recirculating systems to operate the storage device. Possibly prototype hardware for facility tests resulting from such a program could also be available at that time (1966). As pointed out before, due to the very early state of development of this energy storage concept, the time estimates made can be no more than a rough guide. Acceleration of the program by increased efforts may be possible while delays could occur as a result of presently unforeseen difficulties.

2.4 PARTICLE ACCELERATOR SYSTEMS

2.4.1 Injector Considerations for the Facility

The basic requirement of the positive ion or electron source for the facility is that it provides a monoenergetic "parallel" beam of charged particles for injection into the accelerator tube. Systems of cylindrical symmetry will be considered here and space requirements in the high voltage terminal shall not generally be considered a limitation. Since the system will be operated largely in the pulsed mode, source duty cycle and gas efficiency must also be considered for terminal applications in the proposed accelerator. Since projection analyses have thusfar been restricted to low Z ionic species, largely on the basis of total voltage-velocity requirements as well as target penetration, proton injectors will be treated here and the problems of utilization of the system with a negative ion injector will be excluded.

Several existing high energy accelerators, such as the proton synchrotron and linac, accelerate short pulses of charged particles to high energy so that the duty cycle may be quite small. The injectors used with these systems are well suited for our purposes, in which high peak currents for pulse periods of one millisecond or less are required at low duty cycle; i. e. less than one pulse per second due to the charging and storage limitations of the generator. Table 3 presents a review of those ion sources now in existence

[redacted]

Table 3

A Review of Gas Discharge Proton Injectors

Source Type	Reference	Total Current amperes	V_x kv	Pulse Length	$H_1 : H_2$	Aperture Current Density
Occluded Gas (discharge)	30	0.625	10	~ 10μs	40:0.6	0.74 A/cm^2
"	31	0.400	20	400μs	9:1	1.15 A/cm^2
Hot Cathode Gas Discharge	32	~2.0	100	25 ms	9:1	2.1 A/cm^2
Duoplasmatron	33	~1.0	low	100μs	2:1	6.5 A/cm^2
Duoplasmatron	34	0.120	70	1 ms	7:1	56 A/cm^2
Duoplasmatron	35	0.275	45	d.c.	4:1	7 A/cm^2

which are capable of currents approaching the ampere range. Since only sources of the gas discharge type, (generally referred to as the magnetically confined arc), are capable of the high emission current densities required for the injector application, a survey of the other source types (r.f., P.I.G., spark, etc.) would be academic.

For modest pulse duration, the gas discharge source can be operated in the arc pulsed mode. Coupled with a pulsed gas valve, this injector can lead to relatively high gas efficiencies which are compatible with the pumping capabilities of the tube-terminal assembly of such a machine particularly where very low duty cycles are of interest. The high gas efficiency in pulsed operation is the obvious advantage of the first injector considered, the occluded gas source of Crawford et al. In this geometry, the molecular (and/or atomic) hydrogen is supplied from hydrogenated titanium discs from which the gas is extracted subsequent to triggering by a suitably matched pulse forming network. Gas is injected into the arc only during the pulse period and hence the gas efficiency can exceed that of the externally fed source due to conductance and valving considerations. Since the occluded gas capacity of titanium is very high (400 c.c. at STP/gm of metal), adequate storage poses no problem. Crawford has reported 10^5 pulses at low repetition rates at high output levels with no degradation in performance.[30](see Fig. 10)

It is now necessary to examine the other qualifications of the sources enumerated for the proposed application. The average current density at the emission aperture of the source is a meaningless figure for optical design unless some indication of beam divergence is included. A review of injector-acceleration tube matching considerations is presented in the next section and suggests that considerable effort is required in this area for the optimization of a high current electrostatic machine.

Perhaps the injector most representative of the state-of-the-art of source-tube matching is the 100 ma proton injector described in Ref. 34. With the 0.020 inch diameter aperture used in this source, the beam current

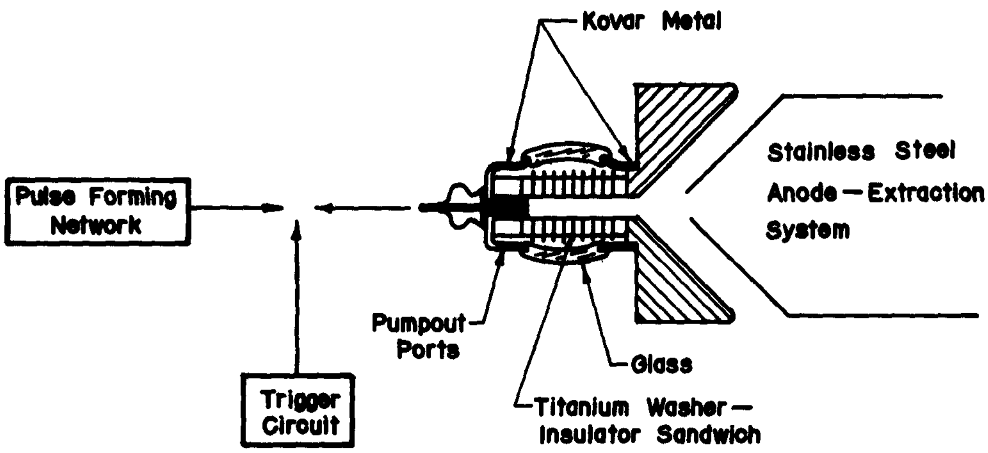


Fig. 10 Occluded Gas Source: Axial Extraction (30)

[redacted]

density at an extraction potential of 70 kv is of the order of tens of amperes/cm^2. Conventional Einzel lenses[36] are inadequate at this level and a wedge tank analog was used for lens design. The lens shape was modeled in the tank and the axial potential obtained. This information was then used for calculation of the equipotential diagram with an assumed beam radius and divergence. From the particle orbit and equipotential data, lens geometries were achieved to adequately handle the beam.

In matching the column to the source, a four electrode lens system was used which would provide an injection energy of 60 kev to a linear-high-gradient column of 538 kv/m. Injection beam requirements were derived by ray tracing backwards through the column and the lens system was then designed to match the extracted output to the tube input. This matching is usually referred to as source emittance - tube acceptance mating and simply stated, requires that the tube can adequately accept and focus the current suplied to it within the phase space area characterized by the source emittance. The above mentioned injector provided an 85 ma H^+ beam with an emittance of 100 mrad-cm in a beam diameter of 1 cm to an accelerator column of calculated acceptance of 179 mrad-cm. The considerations below indicate that adequate computational techniques are now available to permit the design of a matched injector-accelerator system capable of providing proton beam energy fluxes in the 10^2 - 10^3 joules/cm^2/msec, (pulsed power densities of $10^6 w/cm^2$), with a two million volt machine.

Since the facility will also be capable of use as an electron beam accelerator for high intensity pulsed beam propagation and bombardment studies, some comments concerning electron gun optics should be made here. In this case, the techniques of optical design are reasonably well developed.[29, 38] and pulsed electron beams (1μs) of 2 Mev energy have already been realized in the ampere range at this facility. A 20 ampere, 100 kev electron gun or injector can be designed for the facility with existing techniques while an extension to 100 amperes total current is feasible either with the use of existing high current density matrix or field emission cathodes for low duty cycle pulsed operation.

[redacted]

This study has served to point up the inadequacy of present beam diagnostic techniques for injector evaluation with low divergence, high current density beams. Emittance measurements are usually accomplished[39, 40] through the insertion of variable position apertures directly into the beam and scanning of the beam at a plane downstream for determination of the beam divergence characterizing that portion of the beam. Any of these systems suffer from the perturbations induced due to physical interruption of the beam, the associated secondary particle effects and beam potential distortion. These effects are not considered serious at low beam current densities while their application to high intensity pulsed beams becomes difficult and the results highly suspect. Other indirect techniques must be developed for pulsed beam study if reliable emittance measurements in the μrad-cm region of interest for prototype charged particle projector studies.

2.4.2 Beam Focusing During Acceleration

In a fixed-voltage particle accelerating system, the power delivered to a target is directly proportional to beam current, which is chiefly limited by the mutual repulsion among the beam particles, the so-called space charge force. The essential problem in accelerating high currents is the design of electrodes with focusing properties which offset the space charge force in such a way that the beam leaves the accelerating system with suitable diameter and divergence. In order to define the problem more precisely, it is necessary first to discuss the practical constraints within which the problem must be set.

In present Van de Graaff machines, since the high voltage terminal and charging belt are insulated from the containing vessel by gas under pressure, it is necessary to provide a vacuum path from the terminal to ground for beam acceleration. The vacuum tube is usually constructed of a series of conducting discs separated by glass ring insulators and having holes in their centers through which the beam may pass. The discs are tapped into a resistor bank between the terminal and ground in such a manner that the potential is graded uniformly along the tube. The constant gradient insures maximum insulation strength for the tube. In addition to the potential grading, the discs also serve to prevent charge accumulation along the tube and to shield the beam from extraneous influences. The vacuum tube constitutes a leakage path from the terminal to ground. The volt-ampere characteristic of this path typically exhibits current run-away when the voltage exceeds a limit which depends on the geometry and length of the tube. The reasons for this phenomenon are not yet completely understood and none of the various possible explanations will be detailed here. Suffice it to say that current run-away leads to overload of the high voltage supply and must be avoided. Thus, for a tube of fixed geometry, there exists a minimum length for each voltage. The standard tube geometry used by HVEC requires somewhat over one meter to stand off 2 MV without run-away. The large number (over 40) of discs required for such a tube make it expedient that they all be identical and of as simple geometry as possible. This, together with the advisability of linear potential variation, leaves virtually no room for designing focusing properties into the tube. It has thus been natural to think of accomplishing beam forming at low energy in the immediate vicinity of the particle source while performing most of the beam acceleration in the uniform field tube, which has virtually no focusing effect at all.

The beam handling problem is then conveniently divided into two parts. The first of these is concerned with beam flow from the particle source up to a potential of 50-100 kv. In this region, usually of the order of centimeters in length, space charge is of first order importance because the space charge density and force are quite large near the particle source where the beam moves very slowly. The particle source and the electrodes to form the beam in this initial stage of acceleration will be called the injector. The second part of the problem concerns the flow from the injector to the final energy of 2 MV in the (uniform field) acceleration tube. Because the average flow speed in the tube is so very large, the space charge density is rather small so that the force due to it is second order in comparison with the applied force.

Since space charge effects are of primary importance in the injector and only secondary importance in the acceleration tube, the analytical techniques which have been developed for treating each of these stages are quite different.

The problem with the acceleration tube is not one of design but rather one of determining what beam input conditions lead to acceptable output characteristics in the standard tube design. This problem can be solved using ray-tracing techniques with a coarse space charge approximation. Fortunately, suitable computer programs are already in existence at HVEC.[41, 42] They have so far not been applied to beams of the high currents desired in the present application, but there are no conceptual difficulties standing in the way. The first step in high current accelerator design would then be the application of these programs to determine the acceptable range of acceleration tube input conditions.

The problem of designing an injector stage to produce a beam having characteristics within this acceptable range is far more difficult. Suitable analytical tools and the associated computer programs have been under development at IPC for several years. A brief outline of this work as of about one year ago is given in Ref. 43. Achievements since that time have not yet been formally disclosed. However, they enable, in theory, the analytical design of injector stages to any desired degree of accuracy. However, all of the necessary computer programs have not yet been written and there are, in fact, many questions yet remaining about how best to apply the theory from the standpoint of economy of computer usage. Nevertheless, these questions do not prohibit the analytical design of injectors but only stand in the way of improving the techniques presently in use.

The overall acceleration system is current limited by space charge effects in the injector stage. Voltage breakdown limits the strength of the focusing fields attainable in the injector and hence the capacity for compensation of space charge defocusing. Injectors for other applications have already been designed (though not tested) which should be capable of delivering beam currents of up to 0.5 amp of protons or 20 amp of electrons at 100 kv. With the improved analytical tools which can be made available in the near future, it may prove possible to double or triple these currents. It is reasonable to predict that currents of this magnitude can be brought through the standard 2 MV acceleration tube so as to emerge in a well collimated beam with a cross-sectional area of the order of 1 cm^2.

(b) (3) (A) [redacted]

[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted]

F [redacted] (1)

[redacted]

F = [redacted] = [redacted] 2

[redacted] 4 [redacted] → 10 [redacted] 2 [redacted]

[redacted] $\frac{1}{5}$ [redacted] 3 [redacted]

F = [redacted] → 1. 75 x 10 [redacted]

[redacted]

[redacted] 0 [redacted] 8 [redacted] 10 [redacted]

[redacted]

(b) (3) (A) [redacted]

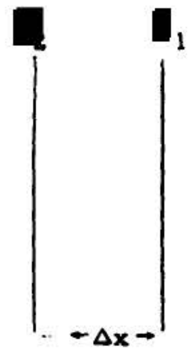
[redacted]

[redacted] = [redacted] K $\frac{[redacted]}{\partial x}$

[redacted] ∂x [redacted], [redacted]

Δx [redacted] $\frac{T_2 - T_1}{[redacted]}$ [redacted] $- K \Big[\Big(\frac{\partial T}{[redacted]} \Big)_2 - \Big($ [redacted] $\frac{\partial T}{\partial x} \Big)_1$ [redacted] $\Big]$

[redacted].



[redacted]

[redacted]

$\frac{[redacted]}{\partial t}$ - [redacted] $\frac{\partial^2 [redacted]}{\partial x^2}$ = [redacted] [redacted]

[redacted] 0 [redacted], [redacted] [redacted] $_h$ [redacted] $_h$.

[redacted]

[redacted] $_o$ [redacted] $\frac{[redacted]}{2\sqrt{Dt}}$ [redacted]

(b) (3) (A) [redacted]

(b) (3) (A)
[redacted]

[redacted]

[redacted] Material	[redacted] h cal/g	[redacted] ρ g/cm^3	[redacted] K cal/sec °C cm	[redacted] D cm^2/sec
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

[redacted] 2 [redacted]

[redacted]

(b) (3) (A)
[redacted]

[redacted]

$$[redacted] = c_\ell [redacted]$$

$$\frac{\partial [redacted] \xi_1}{\partial t [redacted]} = c_\ell^2 [redacted] \xi_1$$

$$\xi_1 = \frac{[redacted]}{E} [redacted]$$

[redacted]

c_ℓ [redacted]

[redacted]

[redacted] [5] [redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

[redacted]

ξ_1 [redacted] E [redacted]

[redacted]

[redacted][2] [redacted]

[redacted] = W [redacted] (14)

[redacted][8] [redacted]

(b) (3) (A)

[redacted]

$$\xi,\text{[redacted]} \; \text{[redacted]}, d\,\text{[redacted]}, = \frac{1}{2}\,\text{[redacted]}\left(\frac{\xi,_{max}}{\ell}\right)^{\text{[redacted]}} = \frac{\text{[redacted]}}{2}\;\frac{F^2\text{[redacted]}}{E} \quad \text{[redacted]}$$

[redacted]

(b) (3) (A)

[redacted]

Table 5

Some Characteristics of Structural Materials

Density ρ	Material	Atomic Weight A	Expansion Coefficient $\alpha \times 10^{-5}$	E $kg/cm^2 \times 10^5$	G $kg/cm^2 \times 10^5$	Tensile Break F_{max} $kg/cm^2 \times 10^3$	Melting Point °K	ΔH kcal/mol
2.7	Al	27	2.0	7.0	2.3	2.0	940	68
9.0	Cu	64	1.4	12.0	4.0	2.8	1350	73
8.2	Mo	96	0.49	30.0	15.0	28	2900	
17.7	W	184	0.42	36.0	14.0	42	3650	
15.4	Ta	181	0.69	20.0		9.3	3270	
2.9	Fused Quarts		0.05				1900	
7.8	Steel .67%C	56	1.8	20.0	7.0	7.8	1700	95

(b) (3) (A) [redacted]

[redacted]:

$$[redacted]\,_1 [redacted]\,_2 q^2 / [redacted]^2 \; [redacted] \; b_1 [redacted]_2 \; x \; [redacted]_o^2$$ [redacted]

[redacted] $[redacted]_2$ [redacted] $[redacted]_H$ [redacted] $[redacted]_2$ [redacted] $[redacted]_2$ [redacted] $[redacted]_e$ [redacted].

[redacted]

[redacted])[redacted]

$$[redacted] = - [redacted] \;\; [redacted]$$

$$\frac{[redacted]}{dx} [redacted] - \frac{[redacted]}{E} \;\; [redacted]$$

[redacted].

[redacted]

$$[redacted] = - [redacted] \qquad (19)$$

[redacted]

$$[redacted] = [redacted]_{max} [redacted] \qquad (2[redacted]$$

[redacted]

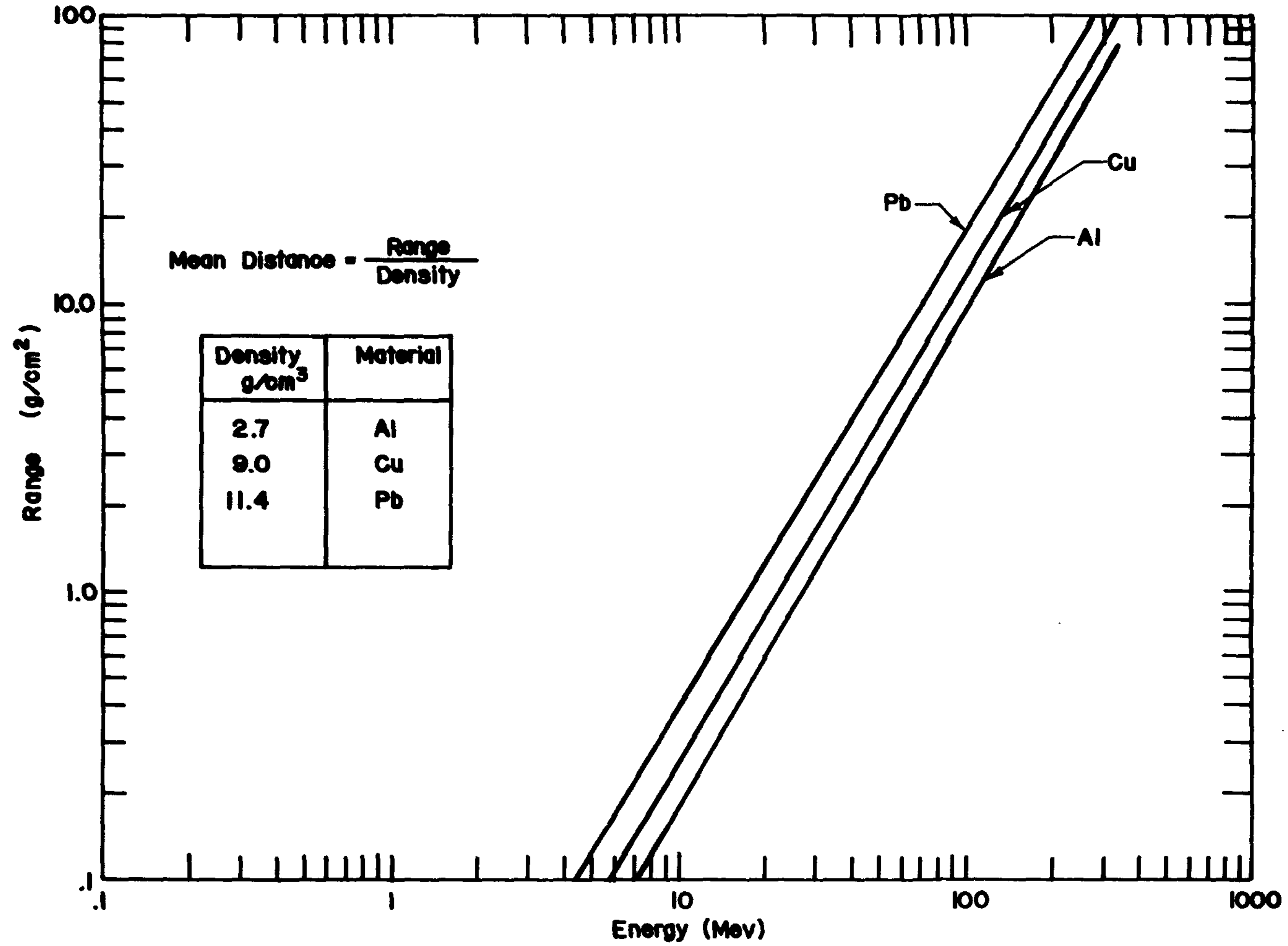
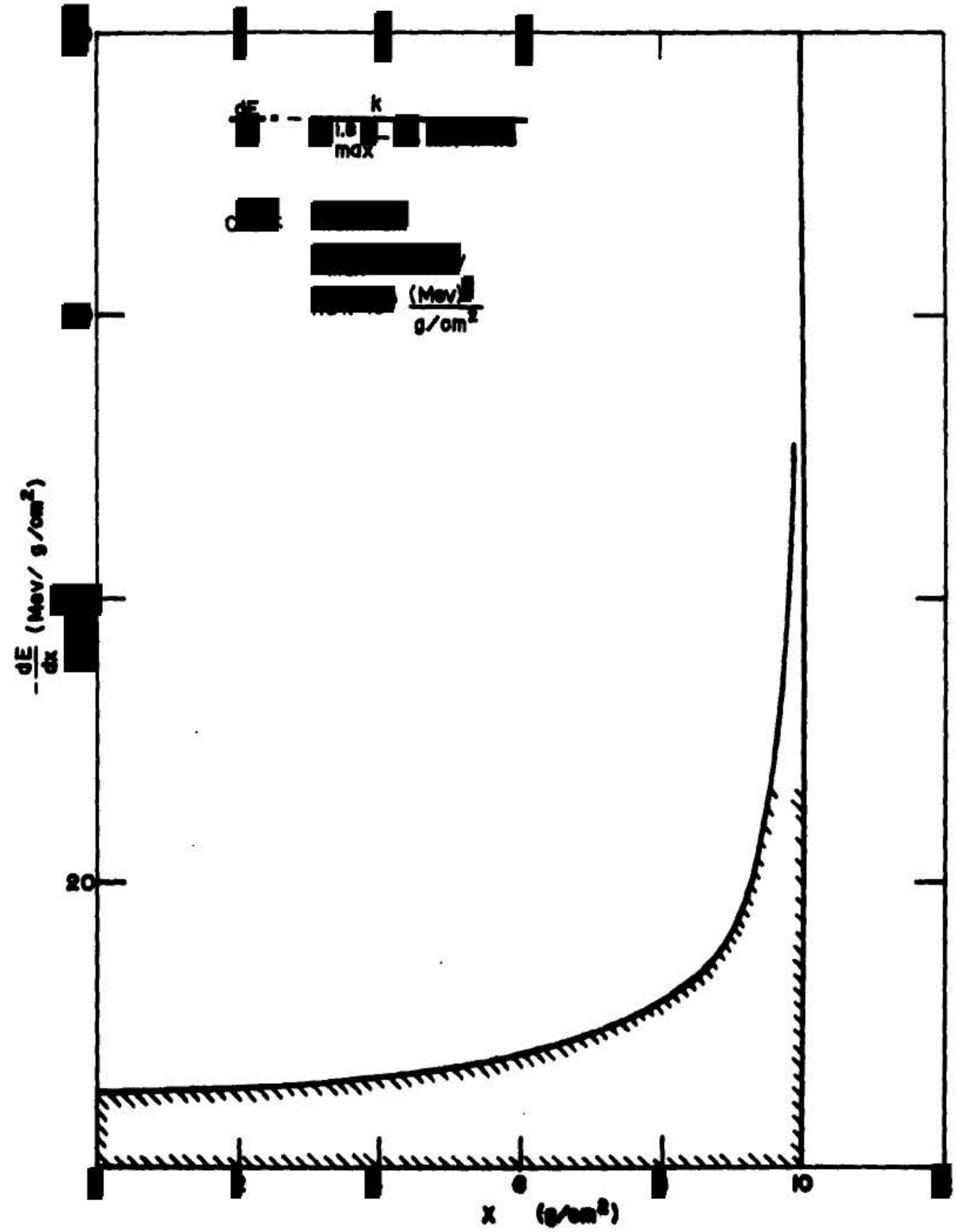


Fig. 12 Mean Range of Protons in Metals

(b) (3) (A) [redacted]



[redacted] s p[redacted] aterial L[redacted] s [redacted]
[redacted] on [redacted] [redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted] = [redacted]

[redacted]

[redacted] = - [redacted]

[redacted]

[redacted] ^{2} [redacted]

[redacted]

[redacted] = [redacted] Δt [redacted]

[redacted]

[redacted] ^{2} [redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted] 2	[redacted]	[redacted] 4
[redacted] -6	[redacted]	[redacted]	[redacted]

[redacted]

[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted]

[redacted] v_p [redacted]

[redacted]

T [redacted]	[redacted] 3	[redacted] 3
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted] 3
[redacted]	[redacted]	[redacted] 3
[redacted]	[redacted] 5	[redacted] 9

[redacted] 3 [redacted]

[redacted] n [redacted]

[redacted]

$$\beta\,[redacted] = \beta\,[redacted]$$ [redacted]

[redacted] β [redacted]

[redacted] $=$ [redacted] $^{1/2}$.

[redacted]

(b) (3) (A)

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

$$a = [redacted] \qquad (30)$$

[redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

[redacted]

$$[redacted] = \frac{[redacted]}{B} \quad [redacted]$$

dx (31)

[redacted]

$$[redacted] = kZ [redacted]^2 \quad [redacted]$$

(32)

[redacted] $_2$. [redacted]

$$[redacted] = [redacted]_o\, a \quad [redacted]$$

tot

[redacted]$_o$ [redacted]

$$[redacted]_o\, [redacted] \quad [redacted]$$

[redacted]

[redacted]

[redacted] Material	[redacted] W_c (Mev)	[redacted] B g/cm^2
[redacted]	[redacted]	[redacted]5
[redacted]	[redacted]	[redacted]1
[redacted]	[redacted]	[redacted]5
[redacted]	[redacted]	[redacted]7

[redacted]$_c$ [redacted] $\frac{dW}{}$ [redacted] ionization [redacted] $\left(\frac{dW}{dx}\right)$ radiation [redacted] . B is

[redacted]$_o$ [redacted].

[redacted]

(b) (3) (A) [redacted]

[redacted]

[redacted] $\left(\frac{[redacted]}{dx}\right)$ [redacted] $\approx$ [redacted]

$\left(\frac{[redacted]}{dx}\right)$ [redacted].

[redacted]

[redacted] $\frac{1}{\nu}$ [redacted] ν

[redacted]

[redacted]

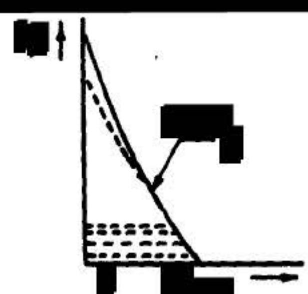
[redacted] ν [redacted] max ν, [redacted]

[redacted]) [redacted]

[redacted]

$[redacted] = [redacted] \frac{[redacted]_2}{h}$ [redacted]

[redacted] is [redacted]



[redacted] ν [redacted] max [redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

[redacted]

[redacted]

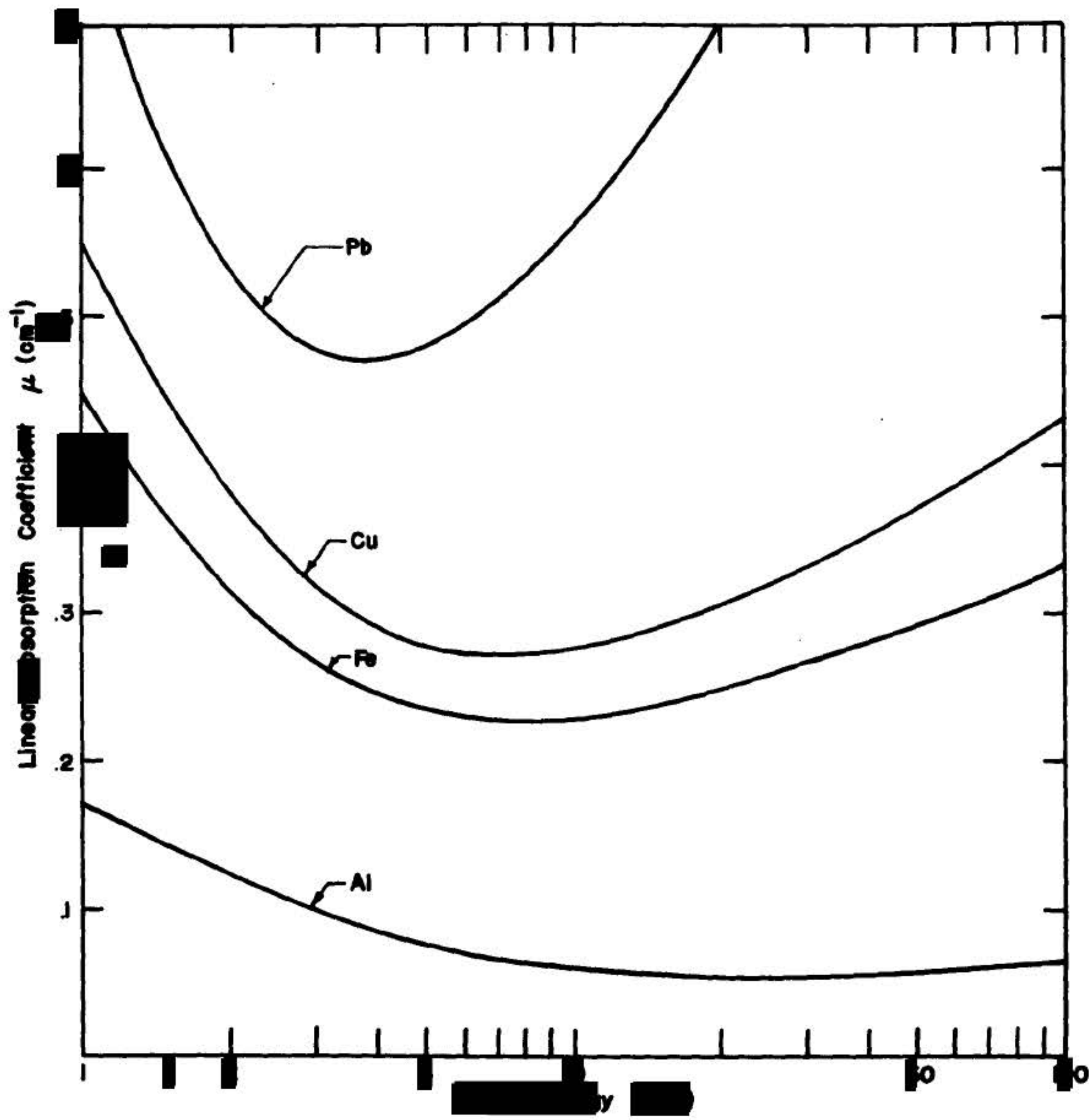
[redacted]

[redacted]

[redacted]

(b) (3) (A)

[redacted]



[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted]

$$[redacted] = -\gamma [redacted] \qquad (38)$$

[redacted]

$$[redacted]$$

[redacted]

[redacted]

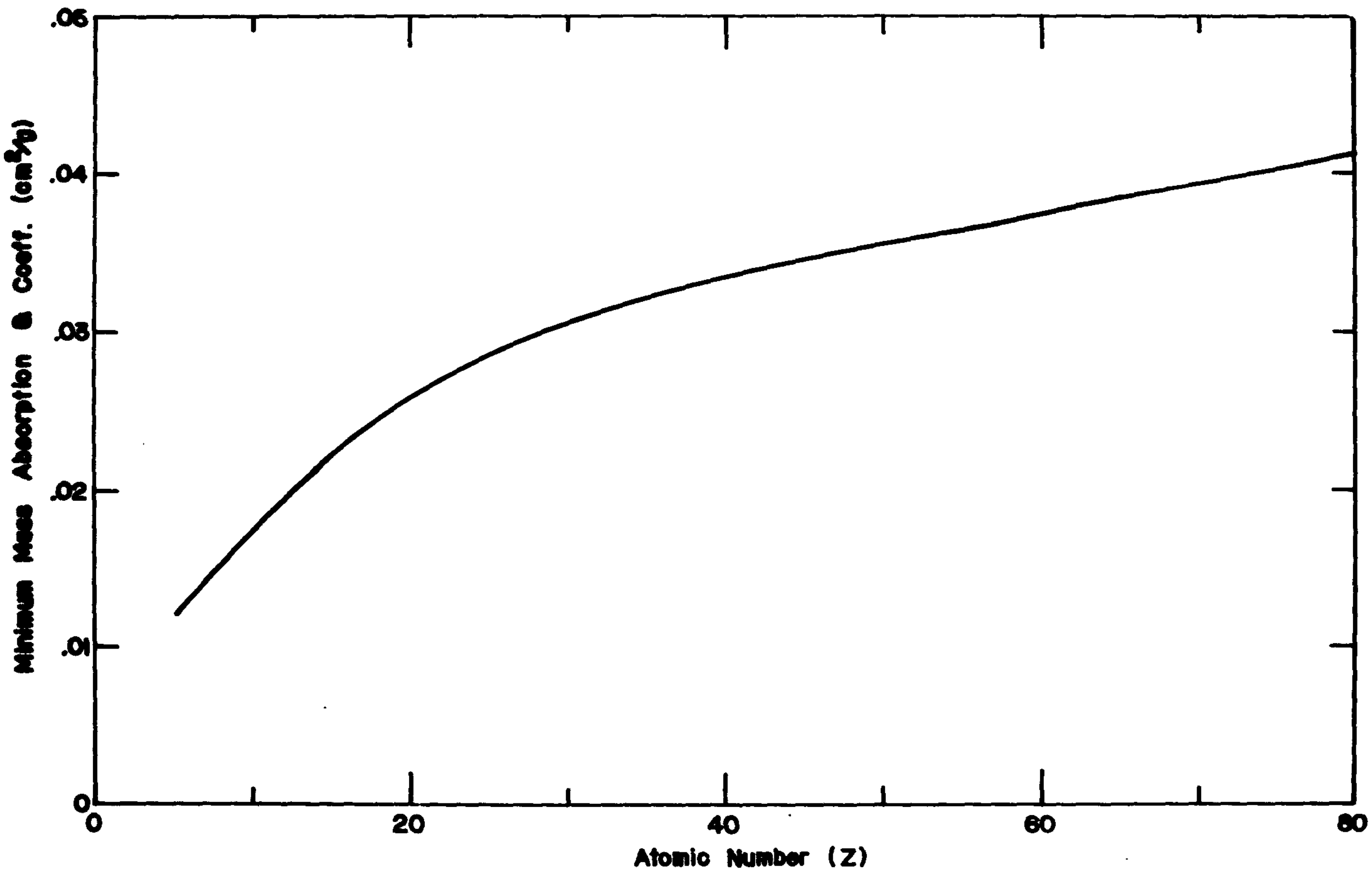


Fig. 17 Absorption Coefficient as a Function of Atomic Number

(b) (3) (A)

[redacted]

[redacted].[52]

$$\frac{W}{[redacted]} = [redacted] \left(\frac{\pi \nu \epsilon}{\sigma} [redacted]\right)^{[redacted]2} \qquad (40)$$

[redacted] $\frac{1}{\Omega m}$ [redacted] $\frac{[redacted]}{W_i}$ [redacted]

[redacted]

$$\frac{[redacted]}{[redacted]} = -\frac{[redacted]}{\delta} \qquad [redacted]$$

[redacted]

$$\delta = \left(\frac{1}{\mu_o \sigma \pi \nu}\right)^{1/2} \qquad [redacted]$$

[redacted]

[redacted] the [redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted] 10^{10}	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

[redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted] [redacted]

[redacted] [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

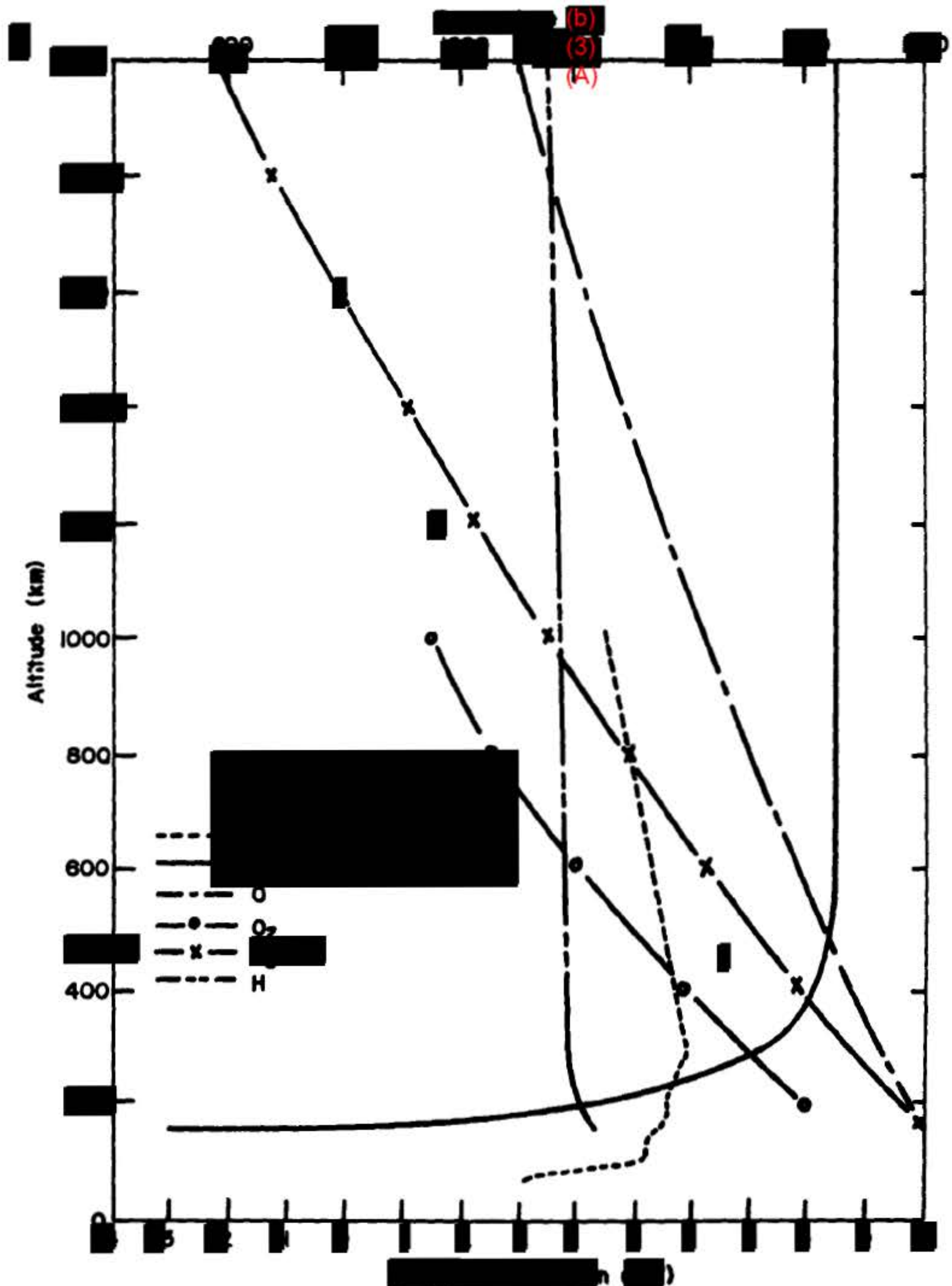
[redacted]

(b) (3) (A)

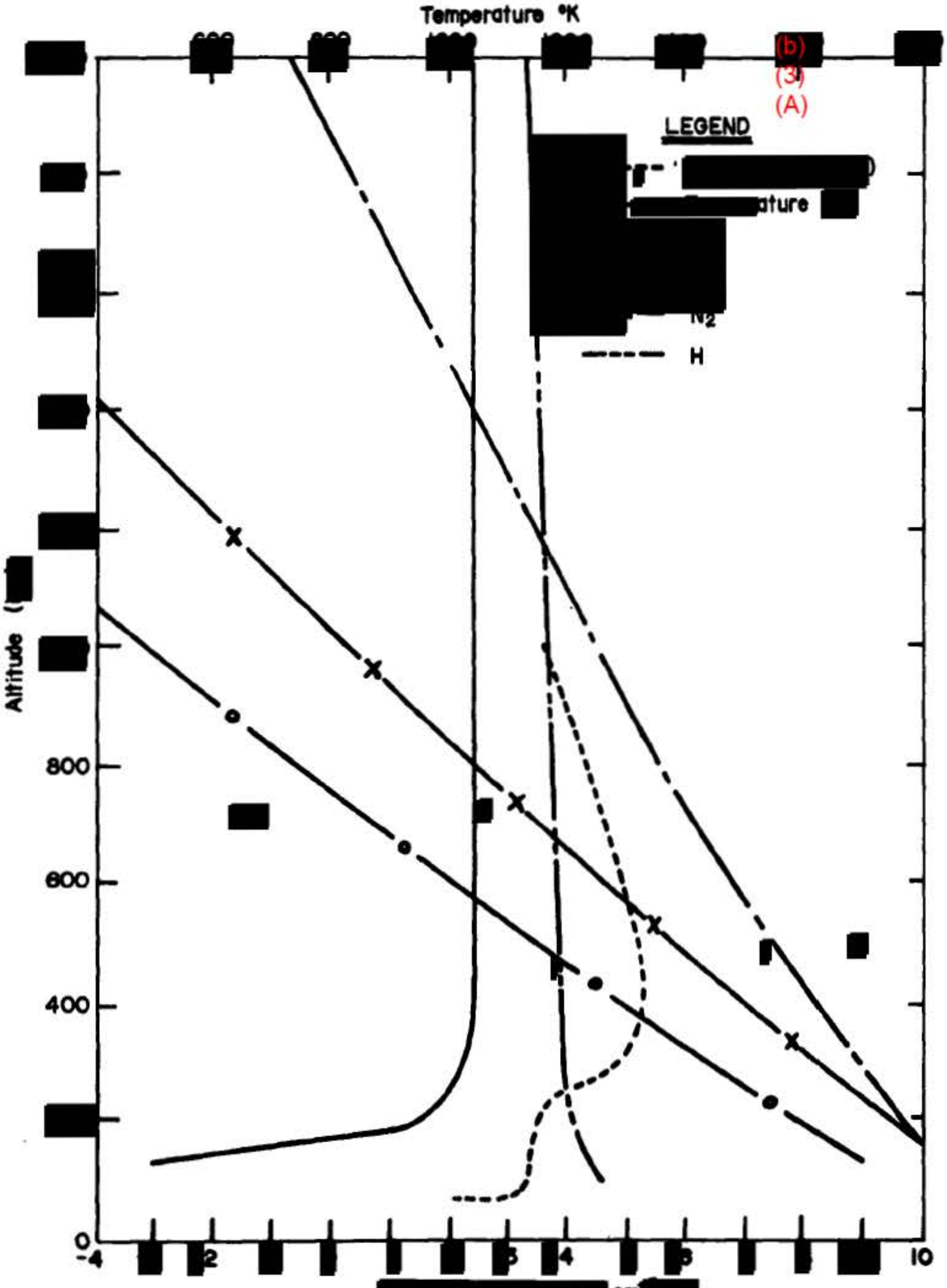
[redacted]

[redacted]

[redacted]



[redacted]



[redacted]

Fig.[redacted] Co[redacted]nstituents [redacted]en [redacted] km
A[redacted]

(b) (3) (A)

[redacted]

[redacted] p f [redacted]

[redacted]

tant [redacted]

[redacted]

[redacted]

(43)

[redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

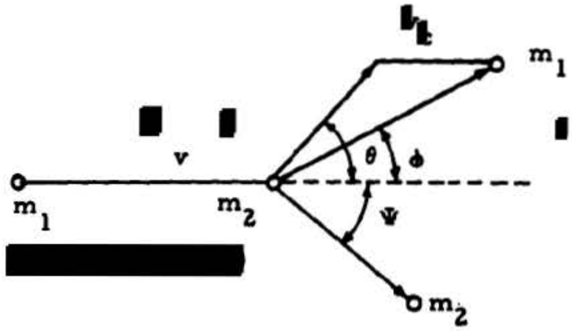
$(Z_2/\beta)\,\alpha >$ [redacted] [redacted]

[redacted] /h [redacted] $\sim a_0$ [redacted] $_2$ [redacted] ^{3} [redacted]

[redacted]

[redacted]

(b) (3) (A) [redacted]



[redacted]

[redacted] = [redacted],
[redacted]

[redacted]

[redacted]

ϕ [redacted]

[redacted]

[redacted]

$T = T_m$ [redacted] $)$

[redacted] E

[redacted]

[redacted]

$M \approx \int_{-\infty}^{+\infty}$ [redacted] $^{-3/2}$ [redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted]

$$[redacted]/2m \approx [redacted]^2 [redacted]^2/m_2 y [redacted] \quad ([redacted])$$

[redacted]

$$[redacted] \left[[redacted] \right] [redacted] \quad ([redacted])$$

[redacted]

$$[redacted] \quad (52)$$

[redacted] γ [redacted] $)$ [redacted] $1/2$ [redacted].

[redacted]

$$[redacted] a], \quad [redacted]$$

[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted]

[redacted] $\approx \zeta$ [redacted]

[redacted]

[redacted] 1 [redacted] $]^{-2}$ [redacted]

[redacted]

$\sigma_T =$ [redacted] π [redacted] $\left(\kappa\right.$ [redacted] $\left.\right)$ [redacted]

[redacted]

[redacted] (57)

[redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted] [redacted]

[redacted]

[redacted]$_s$ [redacted], [redacted]

$$a_s = a_o Z^{-1/3*}$$

a [redacted] $\hbar$ [redacted]$_e$ [redacted] [redacted]

[redacted]

[redacted]

[redacted] [redacted]

[redacted]. [redacted]

[redacted] = [redacted]

[redacted]

$\zeta =$ [redacted]

[redacted] [redacted] ζ [redacted]

[redacted] ζ [redacted]

[redacted]

---

* [redacted].

[redacted]

(b) (3) (A) [redacted]

[redacted]

$$[redacted]\sigma = [redacted]\,f \qquad [redacted]$$

[redacted]

$$[redacted]_\nu\ [redacted]^2\,[redacted]_2[redacted]^2$$

[redacted]

$$\sigma\ [redacted]\ [redacted]_1\ [redacted]_2 \qquad [redacted])$$

[redacted] $_1$ [redacted], [redacted] $_a$, [redacted] $_m$ [redacted] $_a$ [redacted] $^2 = [redacted] / [redacted]^2$.

[redacted] $_n$ [redacted]

[redacted]

$$w = N[redacted]\Delta x\,\sigma = N[redacted]\Delta x\,E[redacted]\,(1/T_1\,[redacted]\,1/T_2) \qquad (62)$$

[redacted]

$$[redacted] \qquad [redacted]$$

[redacted]

(b) (3) (A) [redacted]

[redacted] ^{9} [redacted] $^{-3+}$ [redacted]

[redacted] $_{m}$, [redacted] $_{\alpha}$ [redacted] $_{\alpha}$ [redacted] $^{-15}$ [redacted]

[redacted] 10 [redacted]

[redacted] 10 [redacted]

[redacted]

[redacted] $_{\nu}$ [redacted]

$$\bar{E}_{\nu}\ [redacted]_{n}\ [redacted]\ d\sigma$$

$$[redacted]_{\nu}\ [redacted]_{n}\ \Delta x\ [redacted]_{\nu}\ [redacted]_{m}\ [redacted]_{\alpha}$$

[redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

$\bar{E}$ [redacted] [redacted]

2.60 x 10 [redacted] ev   2.94 x 10 [redacted] ev

[redacted]

[redacted] = [redacted] [redacted]

[redacted]

[redacted] = [redacted] ^{2} [redacted]

[redacted] $_I$. [redacted]:

[redacted]

$$w_I = N_n \Delta x B_\epsilon \Sigma_s (1/T_s - 1/T_m),$$

[redacted] $_s$ [redacted] $_m$, [redacted]

[redacted] ^{2} [redacted] ^{2} [redacted] $_1$ [redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted] ^{2} [redacted]

[redacted]

[redacted]

Δ_ϵ [redacted] I [redacted] Σ_s [redacted]

In [redacted]

[redacted]

[redacted] $/\omega_s$ [redacted]

[redacted] $>>$ [redacted].

[redacted]

[redacted] and a_s [redacted] $< d_s$. [redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

[redacted] (b) (3) (A)

$$T_{m s} = \begin{cases} \text{[redacted]} & \text{: incident protons} \\ 1/4\, m_e \text{[redacted]}^2 & \text{: incident [redacted]} \end{cases}$$ [redacted]

[redacted] except [redacted]

$(\overline{E}_\epsilon)_I$ [redacted]

[redacted]

$(\Delta E_\epsilon) =$ [redacted] (71)

[redacted]

(b) (3) (A) [redacted]

[redacted] $_e$ ^{2} [redacted]

[redacted]

[redacted] $_\epsilon$) [redacted] $\Big\{$ [redacted] ^{2} [redacted] log 1/$\sqrt{[redacted] - [redacted]^2}$ - log 8 + 1/8$\Big\}$ [redacted]

[redacted]

[redacted] $_\epsilon$) [redacted] $\Big\{$ [redacted] ^{2} [redacted] 1 [redacted] $\overline{1 - \beta^2}$ - [redacted] $\Big\}$

[redacted] 2/ [redacted] $_e$ [redacted]

[redacted]

[redacted] ^{2} [redacted]

[redacted]

	[redacted]	[redacted]
[redacted] $_\epsilon$)	[redacted]	[redacted]
[redacted] $_\epsilon$)	[redacted]	[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted] ~ [redacted] π a [redacted] ,

[redacted]

[redacted]

[redacted] 10 [redacted] cm [redacted]

[redacted] 100 [redacted]

[redacted]

[redacted] B [redacted] B . [redacted] n σ [redacted] ,

[redacted] n ~ [redacted]

[redacted] Δx [redacted]

[redacted] 10 [redacted] -

[redacted] 100 [redacted] 5 [redacted] 7

[redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

$$[redacted] \sim [redacted]$$ [redacted]

[redacted]:

$$[redacted] \sim [redacted]$$ [redacted]

[redacted]

$$[redacted]$$

$$[redacted]\ 1.[redacted]^{-26}\ [redacted]$$ (77)

[redacted]) [redacted]

[redacted] is a special case of elec-

[redacted]

[redacted] [72, 73] [redacted]

[redacted] (b) (3) (A) [redacted]

[redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted] then the energy degradation obeys the equation,

[redacted] $\rangle_{ave}$ [redacted]

[redacted]

(b) (3) (A)

[redacted]

[redacted] p [redacted] $^{-3}$ [redacted][7] [redacted] p [redacted] b. [redacted]

[redacted][65, 66] [redacted][67] [redacted] ± [redacted]

[redacted] (1)

[redacted]:

$$\omega_{\pm}^{2} \text{ [redacted] } ^{2} \text{ [redacted] } n_{\pm} ,$$

[redacted][73] [redacted]

[redacted] (2)

[redacted]

$$\omega \text{ [redacted] } = \text{ [redacted] } p \text{ [redacted] } p$$

$$\omega_{b}^{2} \text{ [redacted] }$$

[redacted]

(b) (3) (A)

[redacted]

$$[\text{redacted}]^2 \; [\text{redacted}]^2 \; [\text{redacted}]^2 \left([\text{redacted}] - \gamma \right)$$

[redacted]

$$\omega [\text{redacted}]^{7} [\text{redacted}]^{-1}$$

$$[\text{redacted}] \simeq [\text{redacted}]^{-1}$$

[redacted] k [redacted] [5] [redacted]

[redacted]

[redacted]

[redacted]

[redacted]T

(b) (3) (A) [redacted]

[redacted] $\sim$ [redacted] ^{9} [redacted]

[redacted]. [redacted] $\sim 10^{-19}$ [redacted]

$$\Delta\bar{N} \sim N \; (c \; \text{[redacted]} \; N \; \text{[redacted]},$$ [redacted]

(b) (3) (A)

[redacted]^{1} [redacted]* [redacted]

[redacted] $\sim$ [redacted]^{7} [redacted]

[redacted]:

ω_p [redacted]^{2} [redacted] m_H [redacted]

[redacted]

[redacted] ^{10} [redacted] ^{6} [redacted]

[redacted] $_{0}$ [redacted]

[redacted]$^{-3}$ [redacted]

ω_p [redacted] $_{e})$ [redacted] ^{1}

[redacted]

[redacted] $\left(\text{[redacted]} \pi \; \text{[redacted]} \; \text{[redacted]}^{9} \right) /$ [redacted] ^{7} [redacted].

[redacted]

---

* [redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

In [redacted]

protons), electron, and neutral beam projection from both an absolute tack

[redacted]

following [redacted]

[redacted] $\ell > \ell$ [redacted] ^{2} [redacted] ^{2} [redacted] V [redacted] I

[redacted] ℓ_{cI} [redacted] $_p$ [redacted] $_e$ [redacted] ^{2} [redacted] ,

[redacted] ℓ_{cI}, [redacted]

[redacted] $_p \sim 10^6$ [redacted] $^{-3}$ [redacted] ℓ_{cI} [redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

(b) (3) (A) [redacted]

[redacted]

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(b) (3) (A) [redacted]

(b) (3) (A) [redacted]

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(b) (3) (A) [redacted]

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(b) (3) (A) [redacted]

[redacted]
(b) (3) (A) [redacted]

[redacted]

(b) (3) (A)

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

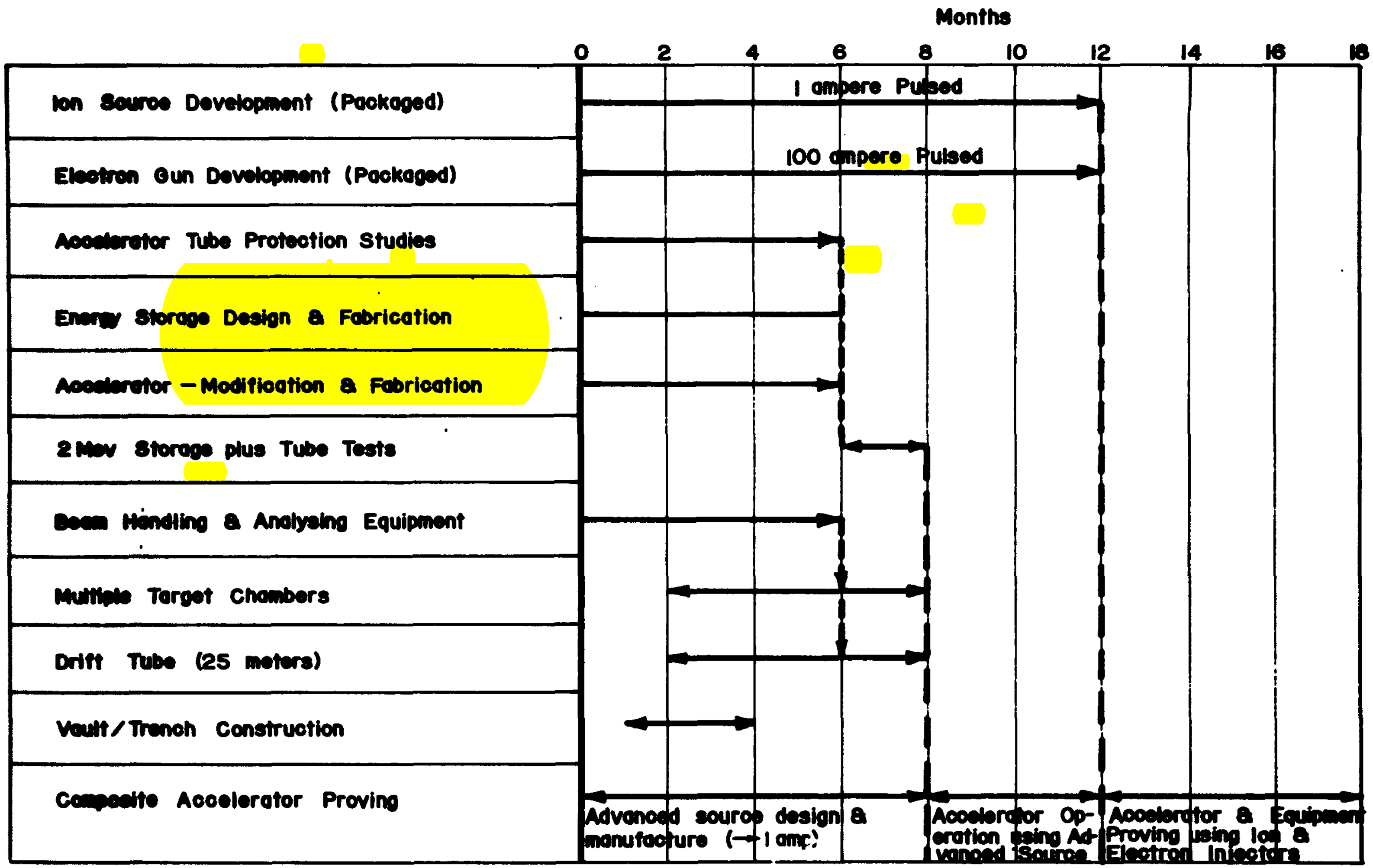
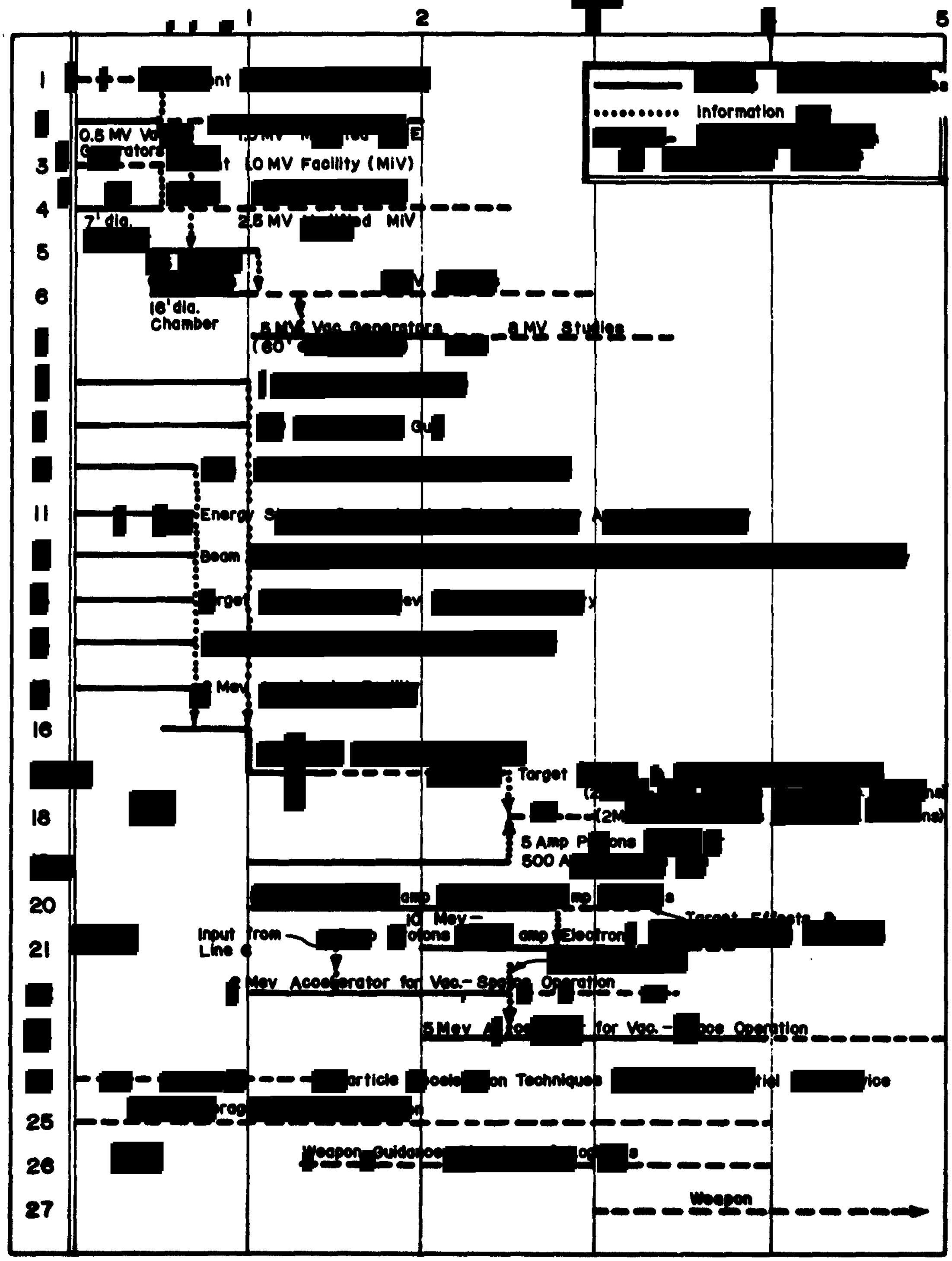


Fig. 21 Program Outline — 2 Mev, 2 KJ Pulse Accelerator (Facility A)

(b) (3) (A) [redacted]



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(b) (3) (A) [redacted]

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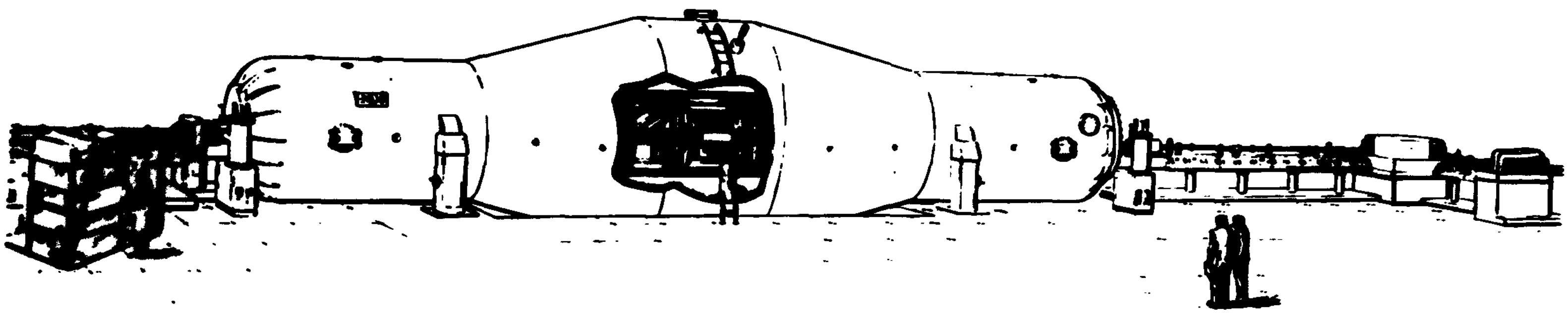
[redacted]



20 MeV Van de Graaff Accelerator

HIGH VOLTAGE ENGINEERING CORPORATION

Fig. 23 Emperor Tandem Accelerator
10 MV Terminal

(b) (3) (A) [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

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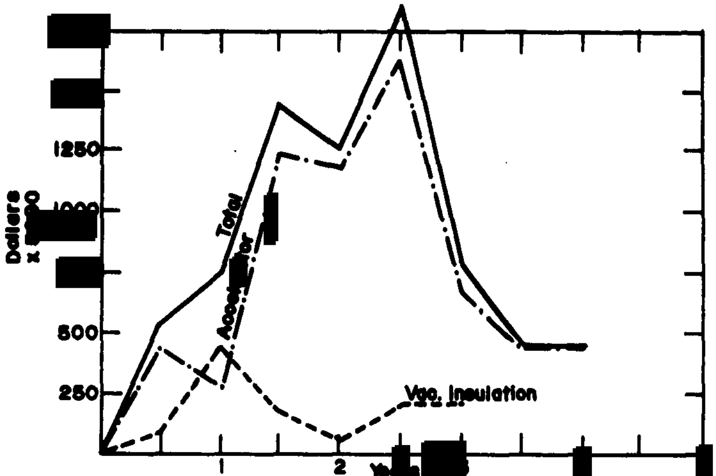
(b) (3) (A) [redacted]



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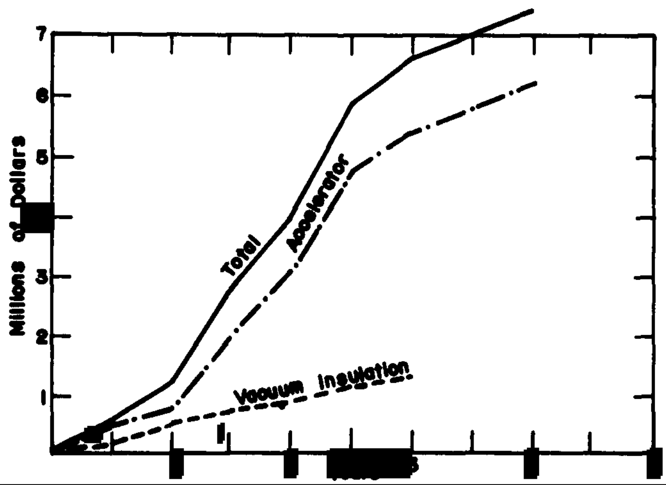
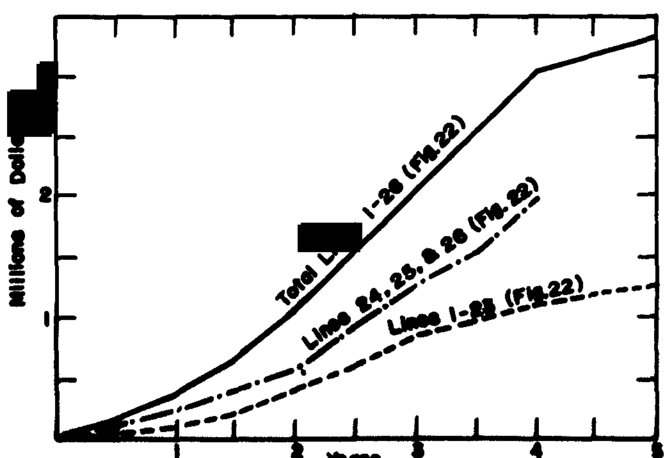


[redacted]



[redacted]

(b) (3) (A)

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[redacted]

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(b) (3) (A)

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[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

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[redacted]

(b) (3) (A)

[redacted]

(b) (3) (A)

[redacted]. [redacted]. [redacted].

[redacted]

(b) (3) (A)

[redacted]

[redacted]

3. FACILITY FOR HIGH VOLTAGE VACUUM INSULATION AND POWER PRODUCTION STUDIES

3.1 INTRODUCTION TO THE PROBLEM

Earlier sections have shown that the most fruitful approach to a directed energy weapon for operation in space is by the acceleration of charged particles. These particles can be accelerated using techniques whereby their travel is synchronized with an accelerating gradient produced by a high frequency voltage at several regions along the length of an acceleration tube - the linear accelerator principle, or by a single potential drop device. The former is not only less flexible but more complicated and the latter is considered the better approach. It becomes particularly attractive if adequate energy can be stored in a reasonable volume at the potentials required for the device. Consequently, the ability to generate and support very high voltages in space is highly desirable. It is expected that potential differences of 10^7 volts or more will be required, with a stored energy of the order of 10^8 joules.

However, the generation and support of high voltages is not easy in the laboratory, and is still less so in space. High voltage insulation problems of a conventional nature are often solved by the use of pressurized gases, and this leads, in turn, to pressure tanks of massive proportions: for example, the total weight of a 5.5 MV Van de Graaff accelerator manufactured by High Voltage Engineering Corporation is 65,600 lbs. of which over 50% is accounted for by the weight of the tank necessary to contain the pressurized gas which insulates the generator from ground. It is therefore an obvious step to examine the use of vacuum as an insulator when high voltages are to be generated and utilized in space. Further, if sufficiently high voltages can be insulated with realizable dimensions in vacuum it would be possible to store the energy required by the

[redacted]

accelerator using the space environment as dielectric. For example, it has been suggested by another contractor under AF08(635)-1636 that adequate energy can be stored in a system of concentric spheres, the larger having a diameter of 80 meters and the smaller a diameter of 40 meters.

Data which is available on the insulating properties of vacuum is fairly profuse, but unfortunately there has been little consistency in the experimental techniques used: furthermore, until recently experiments had only been performed up to 700 kv[75], which is far short of required potential differences. Even at low voltages, the mechanisms of electrical breakdown in vacuum are not understood, although many conjectures have been offered.[76,77,78] For these reasons, it is not possible to design a Directed Energy Weapon to operate at tens of megavolts by extrapolation from existing data, and to obtain better data a research program was initiated under Contract AF08(635)-2166. The contract required the study of vacuum breakdown up to 1 MV. In this, the study has been successful, and the voltage range covered to date has been $250 \leq V \leq 1700$ kv over the pressure regime $10^{-4} < p < 10^{-8}$ torr. A brief resume of the progress under Contract AF08(635)-2166 will be given here since it is most pertinent to the discussions which follow.

The facility which has been built has a vacuum chamber which is cylindrical, 4 ft. long and $2\frac{1}{2}$ ft. in diameter; it contains ports for windows, gauge plates, and the pumping system, which consists of a liquid nitrogen trap, refrigerated baffle, mercury diffusion pump and fore-pump. At both extremities of the chamber there is a pressure tank housing a 1.3 million volt Van de Graaff generator, while a special pressure-to-vacuum high voltage feedthrough bushing communicates the potential of each generator to electrodes in vacuum. The gap between these electrodes can be adjusted in the range 0-60 cm under vacuum conditions. Figure 25 shows the facility, while Fig. 26 shows the basic high voltage bushing.

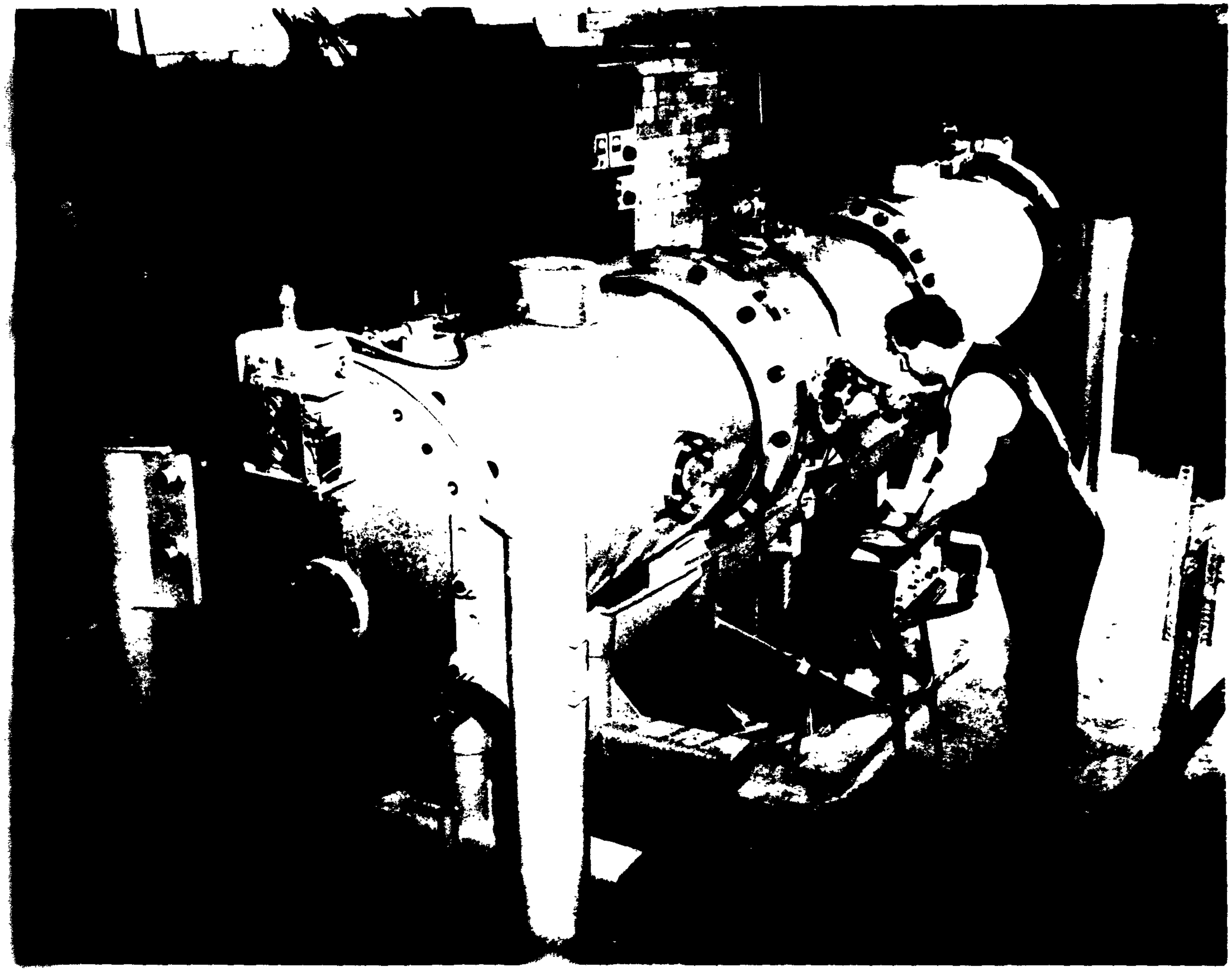

Fig. 25 1 Million Volt High Vacuum Test Facility

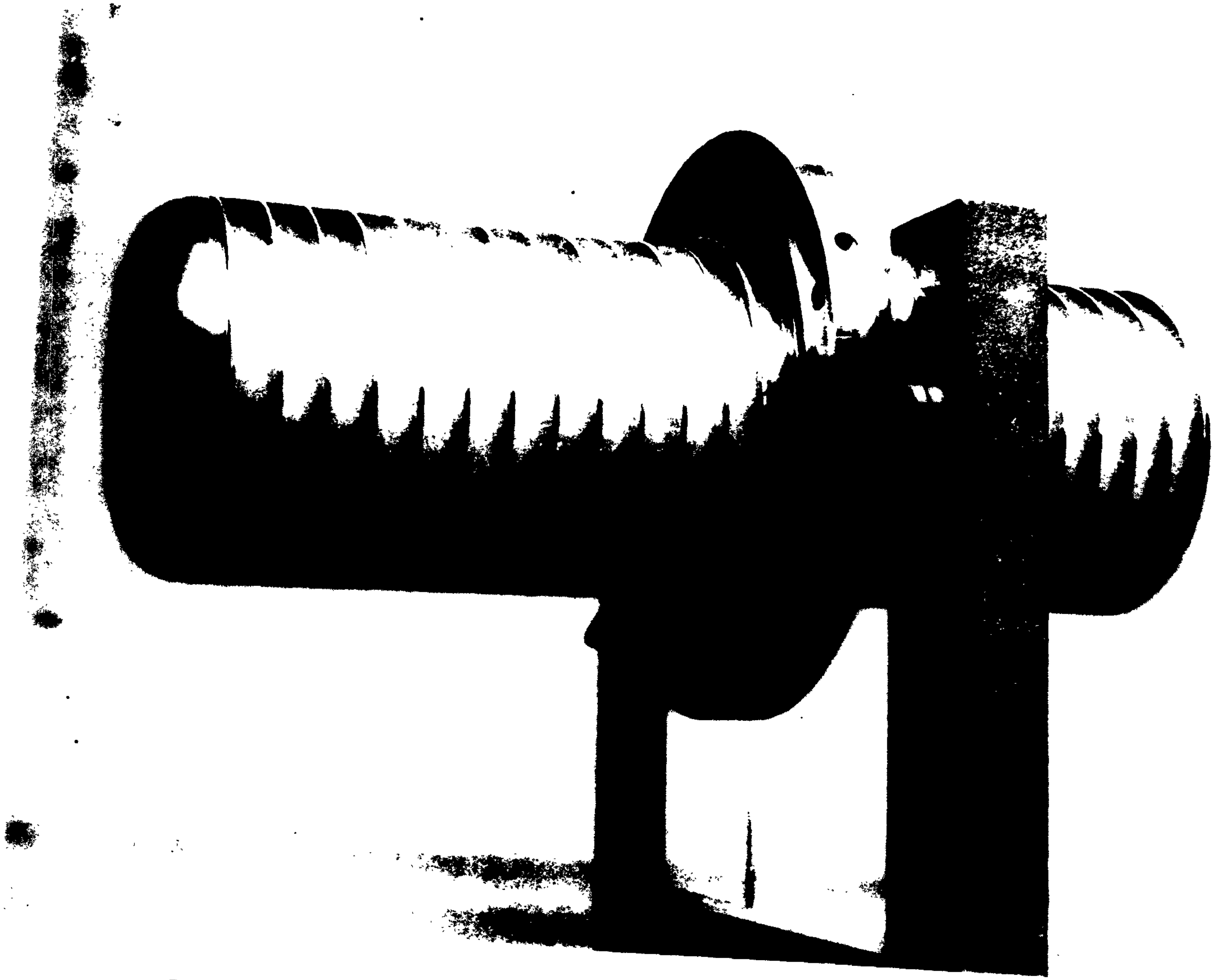

Fig. 26 1/2 Million Volt Pressure to Vacuum Feedthrough Bushing

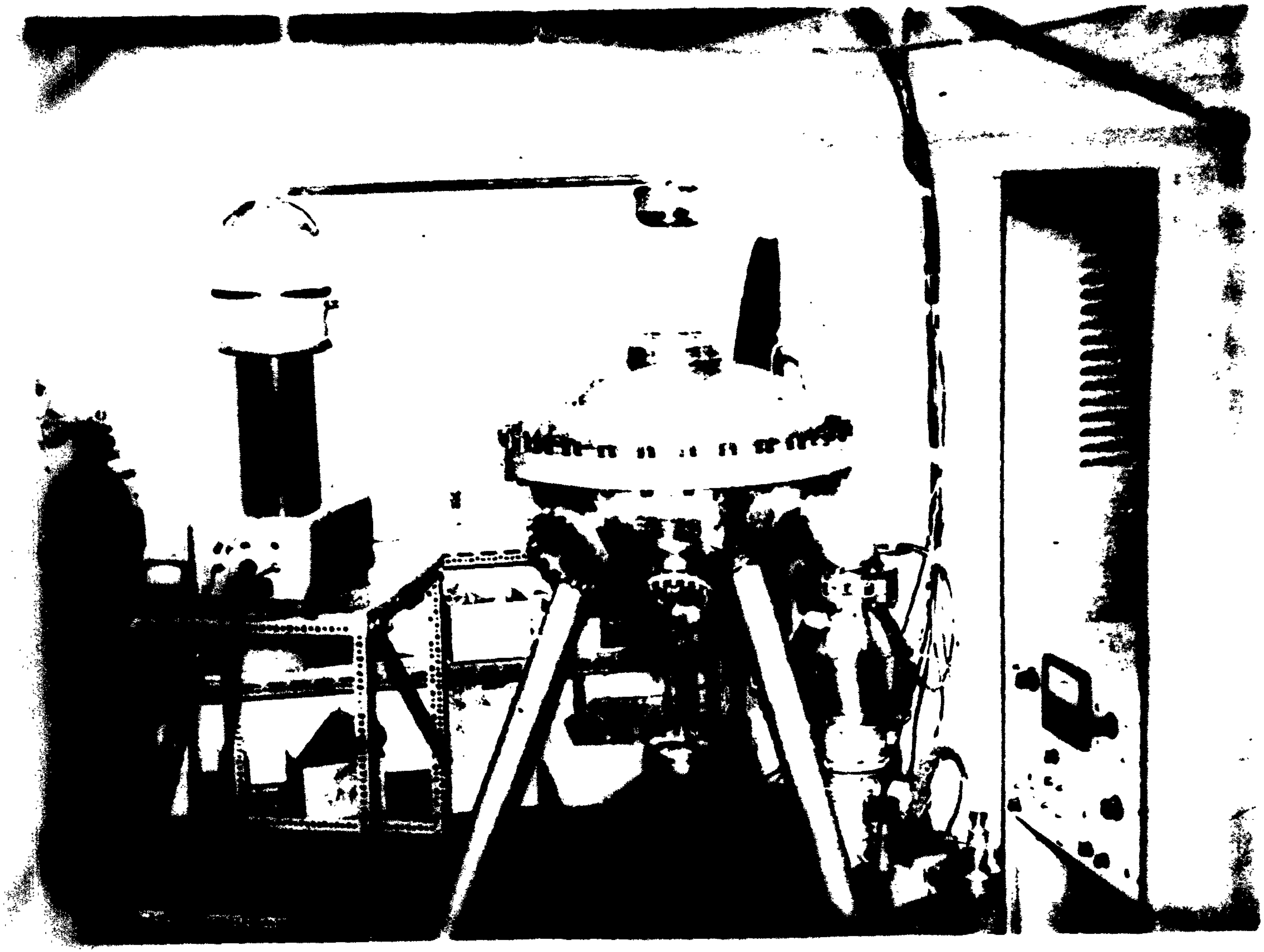

Fig. 27 HIVE Facility

The original requirement was a facility rated at 1 million volts: with generators of opposite polarity, this requires that each bushing supports 500 kv. However, the state of the art at the commencement of this Contract was such that only large ceramic bushings some 3 ft. in length could support 500 kv in vacuum, so that for compactness and reliability, the first step in the Contract had to be the design and manufacture of two h. v. bushings of smaller dimensions and of superior performance to the ceramic type. As Fig.26 shows, the final bushing consists of two aluminum-glass stacks bonded to a central flange: both stacks are insulators, one operating in vacuum and one in the pressurized environment of the generator. A central shaft electrically connects the two extremities of this bushing, which are at high potential, while the center flange is at ground potential, and bolts to the end-plates of the vacuum chamber. Both stacks are voltage-graded internally by means of a cylindrical urethane resistor which carries a current between the high potential ends of the bushing and ground. This resistor is connected at various positions along its length to the aluminum rings in the insulating stacks, so that the potential of these rings is fixed and a uniform electric field exists along the exterior of the insulating stacks.

Considerable effort has gone into the development and modification of this bushing, and of its urethane resistors, and such a bushing has held 1.2 million volts in vacuum at $p \sim 10^{-4}$ torr, and 800 kv at $p \sim 10^{-7}$ torr, voltage levels which are well over the contractual obligations. This can be considered to be a minor breakthrough in the state-of-the-art, in particular when it is noted that the dimensions of this bushing are less than one-third those of a ceramic bushing necessary to support half the voltage. It is felt that this success shows that the development of similar bushings to support 5 million volts is perfectly feasible.

Although a major breakthrough in the ability to support very high voltages at high field strengths across vacuum insulated gaps has not been achieved, there are indications that this may not be altogether out of the question. It has, for example, proved possible to support about 1 million volts

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across a 1 cm gap between a 1/8" diameter positive sphere and a plane, where both electrodes were of 304 stainless steel and buffed to a good polish, and the ambient pressure was $p \sim 10^{-4}$ torr. Under these circumstances, the macroscopic electric field at the surface of the sphere was $\sim 7 \times 10^{6}$ V/cm. Other experiments have examined vacuum breakdown voltages V as a function of interelectrode gap d for different materials, for similar materials with different surface finishes, for different organic and non-organic coatings on cathodes, for different electrode geometries, etc. Still further experiments have investigated bushing modifications and improvements with the aim of evolving design criteria for high voltage equipment in vacuum.

Besides the nominally 1 million-volt facility, a second facility at present rated at 400 kv, has recently become operational. This is termed the HIVE system because it will be used to examine breakdown phenomena in high vacuum at high electric field strengths. The system is shown in Figure 27. This facility will be used to determine the effect of various electrode materials, residual gases, etc. Data acquisition should be much faster with this smaller system.

It is felt that the achievements to date under Contract 2166 indicate that continued research on vacuum breakdown phenomena is justified, and is likely to contribute substantially to the Directed Energy Weapon Program. In addition to the support of high voltages at high field strengths between vacuum insulated electrodes, one of the most important aspects of this program is the generation of high voltages in space. There are several likely DOD applications of accelerators in space where the technology for externally vacuum insulating would be of great utility for packaging for minimum mass. In this context the inverted Van de Graaff generator[78, 79] is relevant. This is a Van de Graaff generator built inside a voltage-graded accelerator column in a pressurized gas, while the outside of the column is in vacuum. The investigation and development of this type of generator is a logical step, based on the technology

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already developed under the present contract, and is discussed in more detail later. Other topics pertinent to the Program include energy storage at high voltages, and the improvement of acceleration tubes beyond the present rating of 0.5 million volts per foot.[80]

However, such research is also important to other projects, one of which is the use of electrostatic shielding to protect personnel and equipment from harmful radiation in space. This concept has recently been examined[81] for a pair of concentric spheres (the inner sphere being the shielded volume) in the environment of the inner Van Allen belt, where the radiation hazard is due principally to relatively low energy protons. If a large potential difference exists between the spheres, the inner sphere being positive, a large fraction of the incident proton flux may be prevented from reaching the inner sphere because of their interaction with the applied electric field. It is clear that both present and future research on vacuum breakdown phenomena, and the generation of high voltages in space, is highly relevant to this program.

This research is also currently of importance in the design and development of high energy particle separators. In this apparatus, an incident beam of charged particles passes between and parallel to a pair of electrodes which may be as large as 3 ft. wide and 30 ft. long. The electric force on the particles is counteracted by the application of a magnetic field at right angles to the beam and the electric field, in such a way that selected particles are undeviated, while the remainder are removed from the beam.

In conclusion, it is apparent that a continuation of this research is directly relevant to the Directed Energy Weapon Program. Progress under the present Contract 2166 is such that it is likely that continued research at present and higher total voltages will greatly improve the state-of-the-art of the weapon, as well as being pertinent to other projects which include electrostatic shielding for space vehicles, and the selection of high energy nuclear particles.

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3.2 PROGRAM - GOALS AND APPROACH

3.2.1 Goals

The characteristics of the facilities for research on high voltage phenomena and the development of high voltage components for the space environment are obviously determined by the required programs. The prime aims of these high voltage vacuum research and development programs may be expressed in the following goals; the first group containing scientific and engineering groundwork and the second group, application of this groundwork to the invention and development of new devices for use in space.

I. Fundamental Investigations

a) Theory - Explanations for the complete vacuum breakdown mechanism, both through the volume of vacuum and along the interface (surface) between vacuum and a solid insulator.

b) Materials - Conductors for support of intense electric fields in vacuum. Conductors for support of large total voltages across single gaps in vacuum. Conductive anode and cathode materials for use in the above situations when polarities are fixed. Insulators for support of high voltages or intense fields and which, at the same time, may serve as high strength structural members in vacuum. Insulators having high tensile strength and ductility combined with low outgassing rates in vacuum.

c) Formulae and techniques - Required for the design of high voltage vacuum insulated apparatus and for the optimization of such devices as regards power-to-mass and power-to-volume ratios.

II. Application to Space-Borne Mechanisms

a) Particle accelerator tubes for the generation of high current beams with very large total energy.

b) Electric generators or converters for producing high voltages from mechanical or low voltage electrical power.

c) Energy storage devices capable of rapid discharge at high voltage.

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A perfect understanding of electrical breakdown phenomena in vacuum would open the way for rapid development of new electrode and insulator materials as well as the creation of engineering design formulae. Therefore, it is felt that the early part of this program must lean heavily towa l fundamental research which can unveil this theoretical understanding. Later, when carefully controlled experiments have been performed at the multi-million volt level, and results have become reliable and repeatable, a materials study program should be initiated to produce engineering data on the electrode or insulator characteristics of a large variety of structurally useful materials. With the experience gained from testing a wide range of materials, new formulae may be established for design of either space-borne or terrestrial vacuum insulated equipment.

The applications of high voltage-vacuum research would, of course, be the final goals. Briefly, the technology is required for the construction of particle accelerator tubes in space capable of conducting high current beams and linearly extrapolative in length to any total voltage. In parallel with this, a high voltage generator design also capable of linear extrapolation to any total voltage is desired. For pulsed beam operation, an energy storage device is required -- also in parallel with the accelerator tube and designed for extension to high voltages.

3.2.2 Philosophy of Approach

In planning the future direction of effort on vacuum insulation at the million-volt level, one might review the progress which has been made at IPC to date. A rundown of notable findings is as follows:

1) Cranberg's Relationship for plane parallel-uniform field electrodes ($VE = C$ from which $V = kd^{1/2}$ may be derived)* has been found to hold to 1.7 MV. Previous experiments stopped at 0.7 MV.

---

* In the expressions, V = voltage, E = electric field, d = electrode separations, C and k are constants.

[redacted]

2) k (in $V = kd^{\frac{1}{2}}$) is an inverse function of the area of either electrode. Between two 20 centimeter diameter electrodes, K_{max} is typically 3×10^5 V-cm$^{-0.5}$. If one electrode is changed to an 0.3 centimeter sphere, k_{max} may be as high as 10^6 V-cm$^{-0.5}$.

   a) As determined by sphere-to-plane experiments.

   b) Strongly indicated by biased grid experiments in which 15% area grid -- properly biased -- raised k by 50 to 80%.

3) k is not noticeably affected by electrode finish if $V > 0.5$ MV.

4) Cranberg's Law ($VE = C$) does not hold for asymmetric field configurations (sphere-to-plane).

5) Voltage of the total system is strongly affected by residual pressure, e. g.

   V at 5×10^{-4} torr ~ 50 to 100% higher than

   V at 2×10^{-7} torr.

   The location of this effect -- in the vacuum gap (volume insulation) or along the bushings (surface insulation) has not been determined. (The phenomenon was first noticed at CERN, then also at Livermore, California.)

6) Vacuum gap insulation is virtually destroyed by exposure to a copious source of charged particles (such as those produced by an ion vacuum gauge).

7) Gross electron field emission does not occur until macroscopic fields exceed approximately 10^6 volts per cm.

   a) Determined by computation of fields in small sphere-to-plane geometries.

   b) Also determined by experiments with a series of disc-shaped field intensification electrodes.

In Fig. 28, one may see the importance of the Cranberg Relationship wherein, for any gap and electrode configuration, voltage obtainable is directly proportional to k value. In the list of experimental findings, we have two strong handles on k; namely, area effects and pressure effects. It therefore seems in order to concentrate on these phenomena until they are understood.

Area effects should be studied by further and more exacting experiments with grids and electrical biasing. It should not be too difficult to establish a direct relationship between k and electrode area, when all other system parameters are maintained constant.

Pressure effects should probably be approached from the "particle" point of view. In the vacuum gap, one would expect to find many types of particles: for instance, neutrals of many different species, and ions -- also in various atomic numbers, of both polarities, and at different energy levels. Experiments must definitely be established to study these particles.

The effects of external circuitry (inductive - capacitive - resistive - rectifier networks) on vacuum insulation should also be examined, with special attention being given to changes in electrode conditioning. Examination of the results from this work would almost surely result in improved theoretical understanding of the problem.

The approach to this fundamental program containing rather many experiments is best solved by having several complete and separate facilities -- differing mainly in the voltage range covered. The range at present is from about 10^4 to 1.7×10^6 volts. Extension of this to 10^7 volts would be extremely useful,but, unfortunately, technical problems as well as expense will more than likely limit the voltage of the next facility step to 4×10^6 volts.

An advantage of several complete systems, each covering a different voltage range, is that experiments performed in one chamber may be checked in another chamber, thereby changing a great many wall and circuitry effects which supposedly do not affect the data. If changes in data are noted, their origin may

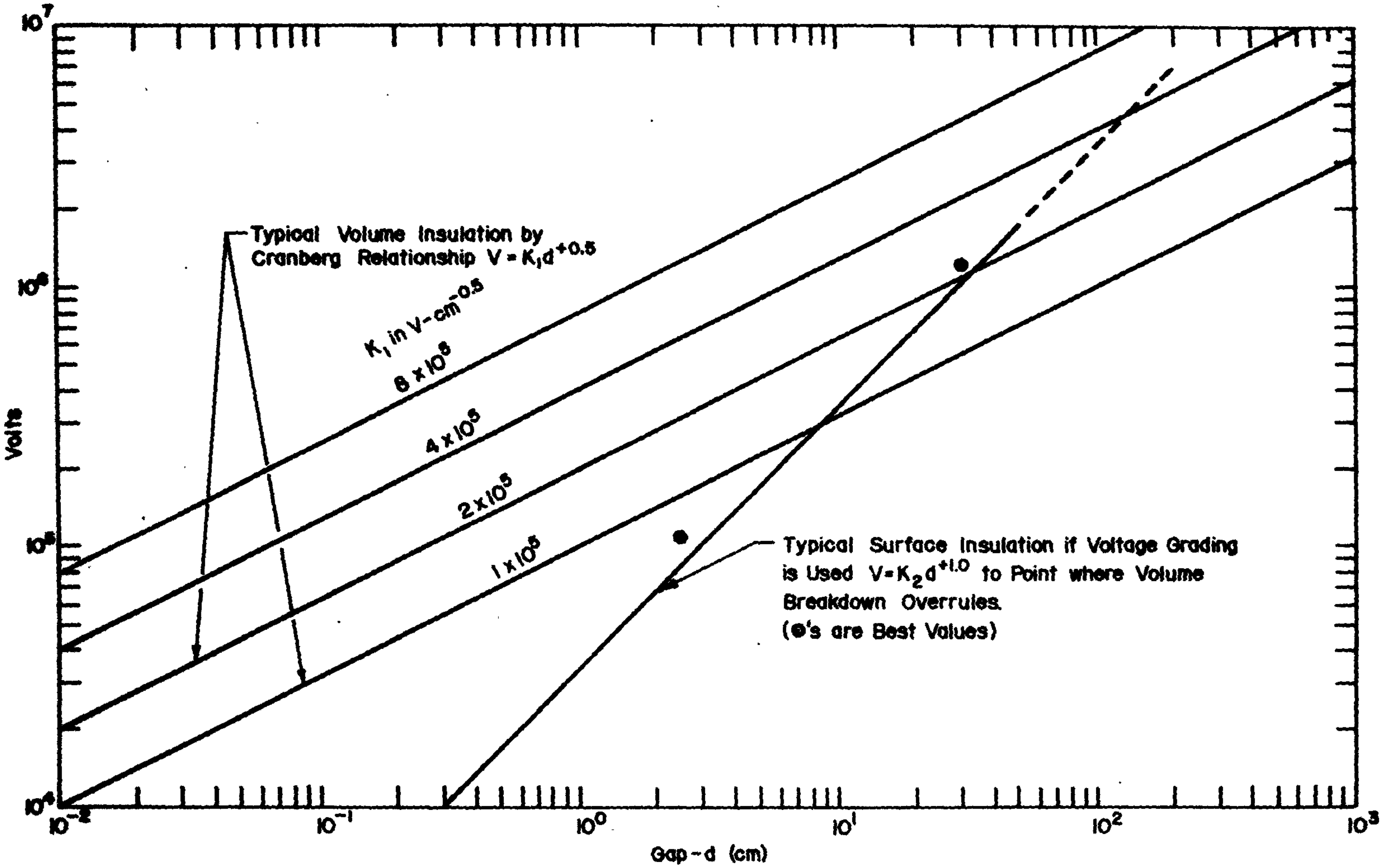


Fig. 28 Voltage—Gap Relationships for Volume and Surface Insulation in Vacuum

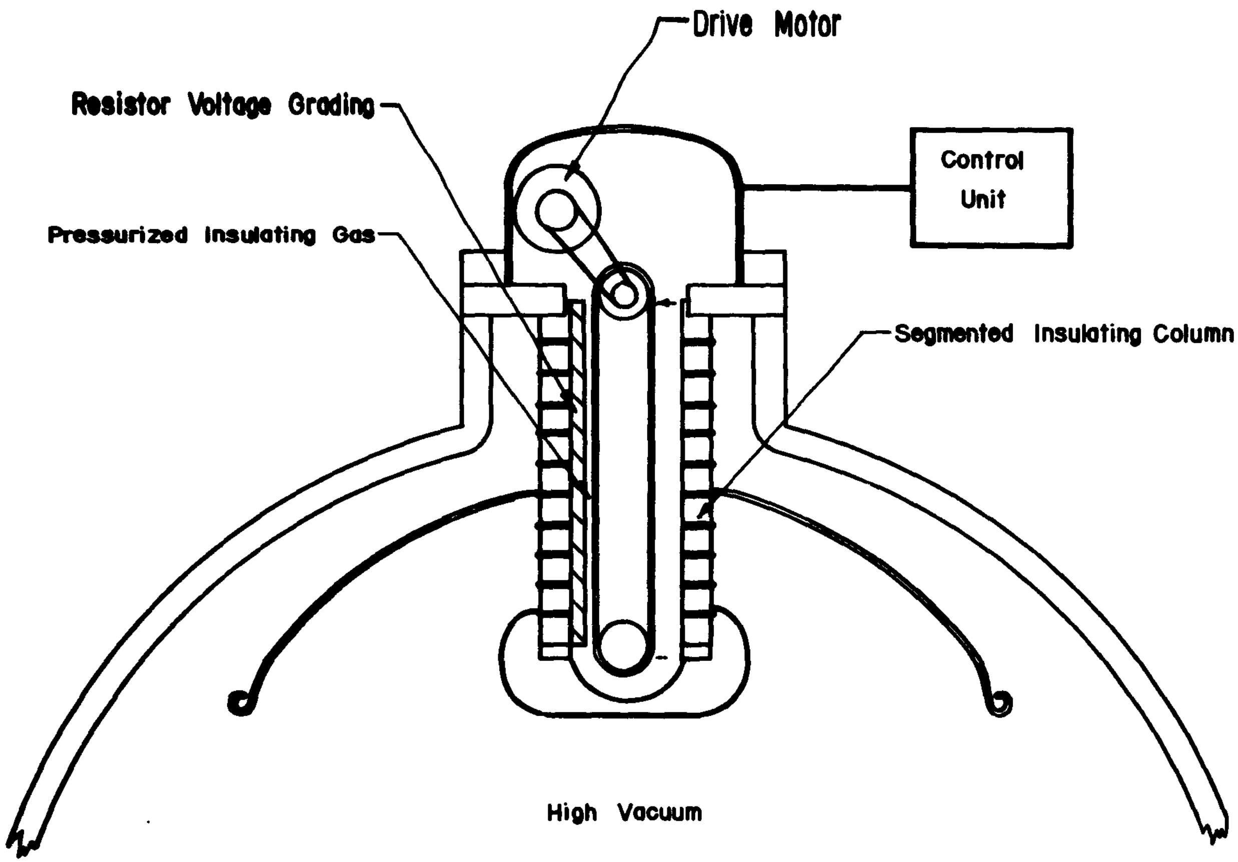
be traced down and eliminated. Another advantage of several systems with different voltage ranges is that a small chamber is more suited to repetitive testing (such as materials testing) where setup time becomes important, while a high voltage and, therefore, large system is more suited to the heavily instrumented, tedious experiment (such as studying charge-to-mass ratio of particles in the gap) in which internal mechanisms may be left in place for long periods.

The applications section of the program may best be handled according to the needs of the device. Power source development, for example, may be carried on progressively from the smallest chamber to the largest, starting with an 0.5 MV design to fit the HIVE (Fig. 29) and moving to the larger systems as voltages demand. Development of accelerator tubes, energy storage devices, and so forth may be carried on in a similar fashion. The two facilities in operation at present, as well as those planned for the future, are equipped with ports, flanges, and vacuum systems of sufficient size, number, and pumping capacity to accommodate the testing of these high voltage devices, with the limit that the design voltage of the device tested may be no greater than the rated voltage of the facility.

3.3 DEVELOPMENT AND DESCRIPTION OF EFFORT

3.3.1 Systems for Developing High Voltage in Vacuum

Apparatus for the study of phenomena at the million-volt level in vacuum has, until recently, been nonexistent except for the special case of the voltage-graded accelerator tube. The closest approach prior to 1962 was probably the experiment by J. G. Trump and R. J. Van de Graaff who, in 1947, reached 0.7 MV in a vacuum chamber of useful dimensions. Because of the difficulties which still frustrate research in this field, an overall review has been made.



Prototype I to be tested in HIVE

Fig. 29 INVERTED HIGH VOLTAGE GENERATOR

The possible methods for producing high voltages in vacuum may be classified as follows:

I. Conventional voltage sources

A. Externally located: High voltage is generated outside of the vacuum chamber by conventional means (e.g. cascaded transformer-rectifier, RF pumped capacitor-rectifier, charge-carrying drum or belt) and conducted into the vacuum with special feedthrough bushings.

B. Internally located: High voltage is produced inside the vacuum chamber by special generators designed to fit and operate within the insulated columns which support the terminals. The generating mechanism could operate by any of the principles presently used for external generation of high voltage as listed in A.

II. Direct particle charging

A. External source: Beams of high energy charged particles (positive or negative) are generated by conventional means (e.g. cyclic accelerators, direct potential drop accelerators), conducted through the wall of the vacuum chamber, and collected in terminals supported on special standoff insulator columns.

B. Internal source: Alternatively, on the insulated terminal one may place a radioactive isotope which, through natural decay, creates high energy charged particles. These particles emanate from the terminal and collect on the vacuum chamber wall, thereby constituting a charging current.

Maximum terminal voltage in either II. A or II. B can approach, but not exceed, the maximum particle energy in Mev.

Surprisingly, all four of these methods have been tried and each has been rather successful. A detailed discussion of each follows.

Conventional Voltage Sources, externally located. This method of obtaining high voltage in vacuum has been the most popular, and is probably the method most likely to succeed if the voltage required is not beyond the capabilities of the bushings. The state of the art, as of January, 1963, for conventional high voltage generators and for appropriate vacuum chambers is, at present, some four times better than the art of bushings.

High voltage generators operating on the belt charging principle are commercially available which will yield 5.5 million volts either positive or negative. The high voltage components of these generators are insulated with compressed gas. Therefore, two of these generators with opposing polarity will yield a potential difference of 11 million volts, but located in a compressed gas environment. It must be further noted that the voltage limit of such generators is normally set by the permissible electric field in the self-contained vacuum-insulated particle accelerator tube. These tubes, until the recent development of the inclined field principle, have been limited to a maximum gradient of about 0.5 million volts per foot. If the accelerator tube is allowed to fill with insulating gas, or else removed entirely, the typical Van de Graaff generator will attain a somewhat higher voltage. With a higher insulating gas pressure and other refinements, one can attain 1.0 MV per foot of column length. With conservative operation, however, one should be able to realize a 50% voltage increase to 8.25 million volts each. This would indicate a maximum potential difference of 16.5 million volts attainable in the gas environment.

Aside from their high voltage-producing ability, belt-charged generators are rather current-limited. At present, the highest current model produces approximately 2 milliamperes. Other conventional generators are commercially available which can produce currents of 10 to 30 milliamperes in the range of 1.0 to 4.0 MV. The Cockcroft-Walton, which operates on the cascaded (series pumped) voltage doubler-rectifier principle, can reach 4.0 MV and 20 ma. The Dynamitron, which operates on the parallel capacitively pumped capacitor-rectifier principle can produce 3.0 MV at 10 to 20 ma. The Insulating Core

Transformer (ICT), which employs the parallel magnetically pumped transformer rectifier principle, can yield 3.0 MV at 30 ma with present designs. Therefore, it may be seen that several methods are available for reaching the multi-million volt level with currents of around 20 ma.

A vacuum system to contain million-volt potentials must have minimum interior dimensions in feet of approximately the intended megavolts squared. (See Section 3.3.3.) This allows reasonable values between terminals and from terminals to walls. The attainable vacuum in the chamber must be better than 2×10^{-4} torr to prevent the occurrence of Townsend type (glow) discharges across high voltage gaps (beginning of the discharge range defined by Paschen's Law).

Vacuum systems have been built with spherical chambers 38.5 feet in diameter and capable of pressures as low as 5×10^{-9} torr. The pressure level is therefore better than the required minimum and the diameter is suitable for a rating of 6.3 million volts. This voltage rating is for an open gap double-terminal configuration such as is sketched in Fig. 34*, and assumes a $k = 3 \times 10^{5}$ V-cm$^{-0.5}$ in the working gap and $k = 2.4 \times 10^{5}$ V-cm$^{-0.5}$ maxima in other areas of the chamber. By addition of potential dividing surfaces such as is shown in Fig. 34, the total voltage may be raised by the square root of two, or to about 8.8 million volts. However, this voltage limit would only be attainable when electrodes were such as to allow a k of 4.3×10^{5} V-cm$^{-0.5}$ in the working gap.

In addition to a power supply and a vacuum system, the third essential to the vacuum insulation facility is a means for carrying the high voltage into the vacuum chamber. This implies the use of a feedthrough bushing. The original effort by IPC (Contract AF08(635)-2166) for obtaining one million volts in high vacuum was, of course, mainly oriented around the development of bushings, since other elements in the system could be readily engineered to the specification. A prototype bushing (Type I) was designed and following approximately six months and several hundred hours of developmental work, it could attain 0.8 MV in <u>high vacuum</u> ($p < 10^{-5}$ torr) and 1.2 MV in <u>optimum vacuum</u> ($p \sim 5 \times 10^{-4}$ torr).

*See page # 138

The data obtained from tests of the Type I bushing (Fig. 26) were used in an improved design (Type II), which is now ready for electrical tests. Photographs of the completed Type I and Type II bushings are shown in Figs. 26 and 35.* Although the Type II bushing has not yet been voltage-tested, the construction features are such that its performance should be slightly better than the Type I. Therefore, a predicted performance in the present vacuum chamber is 0.8 million volts in high vacuum and 1.2 million volts at optimum vacuum. These values are expected with either polarity, which was not possible with the Type I.

It is evident that this general design for a high voltage-vacuum research facility (two gas insulated power sources of opposite polarity, bushings to feed the high potentials through from pressurized gas to vacuum, and a central vacuum chamber for containing the experiments) depends entirely upon the continued development of bushings. Since the present bushings operate at only 0.8 MV in high vacuum, reaching the ±5 MV level implies a factor of six improvement in performance.

A linear extrapolation of the vacuum insulation column of the type I and II bushings indicates that 1.2 MV per foot surface insulation should be possible over a length of three or four feet in optimum vacuum (1.2 MV over one foot has been attained). If additional effort is put on research, it is felt that approximately 1.0 MV per foot could be obtained in high vacuum and extrapolated to a length of several feet (0.8 MV over one foot has been obtained). These extrapolations are made along a curve of slope 1 as shown in Fig. 28. Since the typical vacuum gap breakdown curve has a slope of 0.5, it is necessary that the volume and surface insulation curves intersect at some point as shown in the same figure. For instance, at 5 MV, a Cranberg k of 4×10^5 V-cm$^{-0.5}$ is required to have volume breakdown equal voltage graded surface breakdown. Therefore, one must conclude that around 5 MV or less, a change in slope will occur in the surface insulation curve and above that point, insulator length would have to be increased with the square of the increase in voltage. Alternatively,

*See page # 139

potential dividing surfaces could be used at intervals of 2 or 3 million volts along the insulator column. Potential dividers are shown in Fig. 33.* Unfortunately, the use of potential dividing surfaces is detrimental to vacuum performance because of the large increase in surface area and associated outgassing. Furthermore, the large surface area of the dividers must be electrically conditioned just as any other electrode in vacuum. The electrical effect of this would be a reduction in the working value of k for every increase in area.

The internal electrical design of a 5 MV bushing where the high voltage conductor passes through the ground plane appears to present a more difficult problem than the insulator column design. The electrical insulation which is required to take the high radial stress in this region may be either a solid, a liquid, or a compressed gas. Solid or gaseous insulations are preferred because they are more compatible with maintenance of clean vacuum systems. Gaseous insulations are also preferred over solid because of the self-healing properties of a gas following a breakdown. Furthermore, electrodes in a compressed gas will undergo "positive conditioning" whereas electrodes separated by a solid insulator generally exhibit a "negative conditioning" or loss of voltage-holding ability after each breakdown.

The total voltage at the feedthrough may be supported across a single radial gap. Alternatively, the gap may be split up by the use of potential dividing surfaces, thereby forcing the field distribution. This technique is advantageous where breakdown is strongly field dependent (the usual case in compressed gas insulation) or where breakdown is strongly total voltage dependent (exhibited typically in high vacuum).

Where breakdown is initiated at a maximum field E_m, the maximum voltage (V_m) which can be supported using interpotential shields at optimum radii can be shown to be

$$V_m = E_m R_2 \left(\frac{1 - e^{\frac{1}{k}}}{e - 1} \right)$$

*See page # 137

where R_2 is the outside diameter and k is the number of shells (including the outside). There is little point in using more than two interpotential shields (k = 3) as V_m is then 95% of the maximum possible. There is insufficient information in the megavolt range on solid breakdown and also very little on high pressure gas breakdown. Data supplied by Philp[84] (private communication) has been used to calculate the curves on Fig. 36*; there it can be seen that a suitable coaxial system with a 12" diameter and pressurized at 300 psi of SF_6 can withstand 5 MV. It then remains to develop a glass system which can withstand such pressures at that diameter. A two-phase material approach (glass fibre-glass) looks promising, but may require considerable experimentation to develop a surface-flashover strength equal to that presently attained with vitreous Pyrex glass.

Potential dividing surfaces may also be advantageous where the voltage which can be supported is a function of gap to a power a, and a is less than one as follows:

$$V_{max} = kd^{a}$$

If $a > 1$	Potential dividing reduces total V.
$a = 1$	Potential dividing has no effect.
$a < 1$	Potential dividing increases total V.

This relationship is not true in all cases since electrode area effects must also be considered. For instance, adding a single potential divider shield doubles the active electrode area and this area increase may reduce k such that the total voltage attainable is lessened.

The optimum design of the bushing feedthrough is therefore a rather difficult one, and any design for voltages greater than the present 1.2 MV will have to be followed closely by experimental development. However, our present technical "know-how" seems quite sufficient for the development of bushings to at least the 2.5 or 3.0 MV level.

*See page # 140

The use of conventional voltage sources, externally located, for a very high voltage vacuum facility design therefore hinges entirely on bushing development. Further development is practical up to 3 MV or so. Beyond that point, feedthrough problems become severe, and especially when one considers that the total facility stored capacitive energy can be released across the short radial gap in this bushing if the insulation fails at that point. Stored energy is, of course, proportional to the system capacitance times the square of the system voltage. Because of the voltage limit which can be foreseen, this approach to high voltage vacuum facilities does not present the possibility of extensive advancement in voltage capability.

One further point on this type of facility design is that where very high currents must be obtained in vacuum, this approach is necessary. The external supply can, of course, be increased to almost any required size and power without overloading the bushing current limitation. In our present application, however, such high currents are not needed.

Conventional Voltage Sources, internally located. The inverted power generator, located inside the vacuum chamber, achieves a large reduction in overall space required by the facility as may be seen in Fig. 34 for a typical design. The generators in this facility are located almost entirely within the bounds of the 16 foot diameter spherical vacuum chamber. If external generators were used, they would add some 8 feet each or 16 feet total to the height of the facility in order to achieve the same total system voltage.

The idea for inverting the Van de Graaff generator by putting the belt inside a pressurized column and having the dome and outside of the column in vacuum is not new. However, it has never been developed at the multi-million volt level. A recent design (Fig. 30) by Leo Jedynak at MIT has generated 0.55 million volts at 30 microamps. The column is $5\frac{1}{2}$" diameter by 12" long and fits in a 20" dia. x 28" tall vacuum chamber. These overall dimensions of a one-half million volt generator indicate the capabilities of an inverted machine.

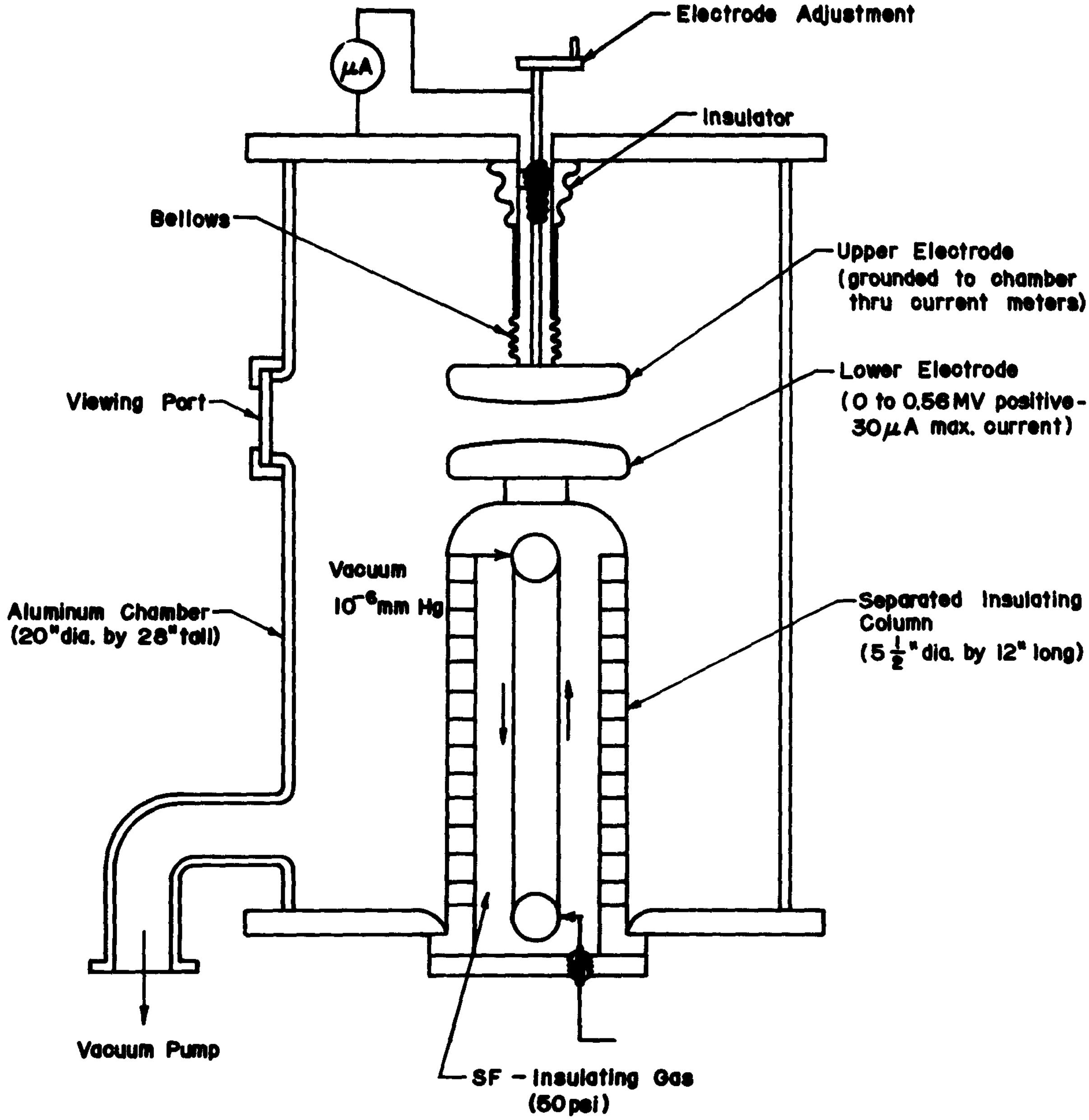


Fig. 30 Conventional Voltage Source, Internally Located Vacuum Insulation Research Apparatus by Leo Jedynak

Further strong reasons for wishing to develop the inverted generator are connected with problems of feeding high voltage into vacuum if a standard generator is employed. As already noted, the high voltage pressure-to-vacuum feedthrough bushing concept can be developed to around 3 million volts with reasonable effort, but the same effort could make rapid advances in the inverted generator design. The main basis for choice between standard generators plus bushings and inverted generators is in power or current required. The present Type I-II million-volt bushing is capable of conducting some 10^9 watts (10^3 amps at 10^6 volts), while an inverted power generator of the same column size could develop 10^3 watts (10^{-3} amps at 10^6 volts). The choice therefore seems to lie at the 10^3 watt level for a 1 million-volt machine.

The current which will be required for high voltage-vacuum research is expected to be small -- probably less than 100 microamperes for vacuum breakdown studies at the 4 Mv level.(Experiments at the 1.5 Mv level generally require only 10 microamperes.) Capability of the inverted power generators is expected to be 1000 microamperes at 4 Mv or at least one magnitude greater than predicted needs.

The belt generator is only one of many methods for producing high voltage which may also be inverted. Other possibilities include the gas insulated Cockcroft-Walton, Dynamitron, and the variable capacitance electrostatic generator. The Insulating Core Transformer would not be so suitable because it is less amenable to packaging in a small diameter column. The electrostatic generator may also be vacuum insulated, thereby offering lighter weight construction. Vacuum insulation is a desired characteristic, in any case, for a system which must operate in space.

Direct Particle Charging, external source. Electron beam charging of an insulated terminal in vacuum has been experimented with at Argonne National Laboratory by De Geeter.

Potentials up to 0.3 MV were obtained in a small vacuum chamber with maximum voltage limited by breakdown to the walls of the chamber.

At 0.2 MV, electron currents of 100 microamperes could be collected with 80 to 90% efficiency. Further experiments in electron beam charging are planned at Argonne in connection with the design for a crossed field velocity selector.

Direct Particle Charging, internal source. Charging of an insulated terminal in a vacuum system by means of a radioactive beta source (Sr^{90}-Y^{90} mixture) has been investigated by J. W. Kennedy, et al, at Washington University, St. Louis.

Potentials of approximately 0.3 MV were reached, at which point prebreakdown currents were equal to the charging current (a one millicurie beta source emits a current of 5.92 micromicroamperes).

Experiments with direct particle or beam charging have certainly proved the high voltage capability of such techniques, especially when one considers that breakdown or prebreakdown currents to the chamber walls limited the peak voltage. Our intent, however, is to obtain a facility in which experiments will not be adversely affected by any stray particles other than the mainly neutral ones which are outgassing from the walls and being steadily removed by the vacuum pump. The particle charging system, therefore, must be discounted since a very small percentage of ions being added to the chamber residual gas could completely upset most high voltage experiments (see Section 3.2.2, Item 6).

3.3.2 Chosen Method

The facility concept which appears to offer the highest prospects for extrapolation to very high total voltages is the conventional voltage source, internally located design. The only problems which are foreseen with this approach are that the vacuum chamber must be unreasonably large for rather low total working voltages (4 to 10 MV). However, the vacuum chamber size is determined strictly by the total voltage and is unaffected by the method for producing or introducing this voltage. Therefore, the chamber size problem would be present no matter which concept is used.

The main advantage of internally located power generators is that increases in voltage can probably be made by linearly increasing the length of the generator (assuming it is a belt charged machine). This increase can continue until volume voltage breakdown occurs from the generator dome to the chamber wall or to the opposing terminal. The approach is also very attractive because it is that required for the development of accelerators in space, making the optimum use of the natural environment.

Investigation of designs for an inverted Van de Graaff by IPC indicates the feasibility of one million volts per foot of column length and 1 milliampere of current in a 9" outside diameter -- exclusive of vacuum insulation to the walls.

Prototype designs of an inverted supply could be developed, for example based on existing IPC facilities, in the following order:

1) A working mockup -- air insulated.
2) An 0.5 million-volt generator to fit the HIVE, gas insulated.
3) If 1) is successful, a second generator of the same size but with incorporation of further ideas.
*4) A 1.5 million-volt generator to fit MiV, using results from 2) combined with Type II bushing column.
5) A 2.5 million volt generator to be tested in MiV-2 (7' diameter chamber) but for use in the 4 Mv system if successful.
6) Ditto of 4) for opposite polarity source.
7) Design of 5 Mv generator for test in 4 Mv system and use in 8 Mv system.

*Note: Step 4) may be omitted if the 7' diameter MiV-2 chamber is completed by that date.

A sketch of an 0.5 Mv - 0.2 ma prototype inverted Van de Graaff generator is shown in Fig. 29. This machine would be designed to fit the HIVE as listed in 2) above. It is expected that all mechanical design difficulties of the inverted generator could be ironed out at the 0.5 Mv level.

Design problems foreseen at the moment are mainly those connected with containment of insulating gas at 200 to 350 pounds per square inch to insulate the internal works of the column to a level of 1.0 million volts per foot of length. A mechanical tension rod which is a good electrical insulator is therefore needed to hold the column in axial compression. Presently available insulating materials are either brittle or their insulating qualities are poor. Tangential stresses in the column rings must be removed from the glass. This can probably be accomplished by increasing the number and strength of metal rings, and by adjusting their modulus of elasticity such that they carry the major portion of the radial bursting pressure.

Other problems in the inverted design will be mainly those of packaging. Their solution, however, is expected to become evident during construction of the initial mockup and 0.5 Mv machine.

The chosen approach is, therefore, to pursue the development of inverted high voltage power generators from the 0.5 to the 2.5 Mv level, at which point a suitable vacuum chamber would be constructed to house two 2.5 Mv supplies and thereby yield 4 to 5 Mv total. Further facility growth will be covered in Section 3.4.

3.3.3 Review of Existing and Proposed Facilities

Vacuum breakdown research at the present under AF08(635)-2166 is carried out in two facilities:

HIVE: a $2\frac{1}{2}$' diameter spheroidal chamber with capability of approximately 0.4 million volts. (Fig. 27)

MiV: a $2\frac{1}{2}$' diameter by 4' length cylindrical chamber with voltage capability of approximately 1.5 million. (Fig. 25)

These facilities, in particular the MiV, are, by a considerable measure, the most advanced vacuum insulation test facilities for the very high voltage range of which we are aware. It is natural, then, that advances to higher potentials should be based on these facilities, and that is the philosophy which has been adopted.

Studies under AF08(635)-2795 have developed concepts for extensions in potential to 4 and 8 million volts in two additional facilities of 16 and 64 foot diameters, hereafter designated as Phase I and Phase II. In addition, it is proposed to undertake certain improvements and modifications to the two existing systems to bring their experimental performance up to the level which has been calculated for Phases I and II.

A basic criterion for experimental value of a vacuum breakdown facility has been determined empirically through experiments in the 1 million-volt system. This criterion is that the minimum chamber dimensions for testing of typical electrode materials up to the full system voltage must be $D = (MV)^2$ feet. For larger chambers, the optimum geometry is a sphere and permits experiments with electrodes of diameter D/2 at maximum separations of D/2 at which condition system design voltages could be attained with a Cranberg value of $k \geqq 3 \times 10^5$ volt-cm$^{-0.5}$ in the gap.

Application of this criterion to this same 1 MV facility reveals that the $2\frac{1}{2}$' diameter x 4' long vacuum chamber places a serious limit on maximum chamber voltage. By replacing the vacuum chamber with a 7.0' diameter sphere,

$$(1.3 \text{ MV V.d.G. supply maximum} \times 2)^2 \text{ feet} = (2.6)^2 = 7.0$$

it should be possible to conduct experiments up to the 2.6 MV level with this facility.

A similar calculation for the HIVE facility with 1.88' minimum dimension indicates that its capability should be 1.37 MV. Since the present bushings for this system are not capable of 1.37/2 MV, small inverted 0.5 MV power supplies could be applied to this chamber to yield a factor of 2.5 improvement in working voltage.

The vacuum breakdown facilities would then stand as listed in the following table.

Facility	Maximum Potential	Nominal Rating	Chamber Min. Dim.	Ultimate Vacuum	Original Operational Date
HIVE	1.37 MV	1.0 MV	1.88'	1×10^{-8} torr	January '63
MiV - 2	2.6	2.0	7.0	8×10^{-8}	March '62 (MiV - 1)
Phase I	4.0	4.0	16.0	5×10^{-9}	October '64 proposed
Phase II	8.0	8.0	64.0	1×10^{-9}	March '65 proposed

HIVE Facility

HIVE, standing for High Vacuum, High Field, is a small, versatile research facility of advanced design (Fig. 31). It incorporates many features essential to high voltage as well as high vacuum which were discovered or proven on the 2 million-volt research apparatus, such as: high polish on interior surfaces, large radii on edges of windows and ports which are reached by electric fields, 304 stainless steel construction (a good electrode material), freedom from organics by mercury diffusion pumping, ceramic bushings, and gold metal gaskets.

Electrodes up to 8" diameter may be changed by removing a window, while larger electrodes or multiple samples on a turntable may be set up by opening the 30" flange. A fast pumping system permits one to reach 5×10^{-5} torr (sufficient for starting voltage tests) from atmosphere within 10 minutes. An ultimate pressure of 1×10^{-8} torr is expected.

Bushings on the HIVE are an IPC design. They operate from atmosphere to high vacuum and initial tests have shown good performance to 0.21 MV in high vacuum. The bushing is of brazed ceramic construction, and is insulated internally by sulphur hexafluoride at 2 atmospheres.

High voltage for the HIVE is obtained from two air-insulated Van de Graaffs which are capable of 0.25 MV and 100 microamperes each, and which include polarity reversal switches.

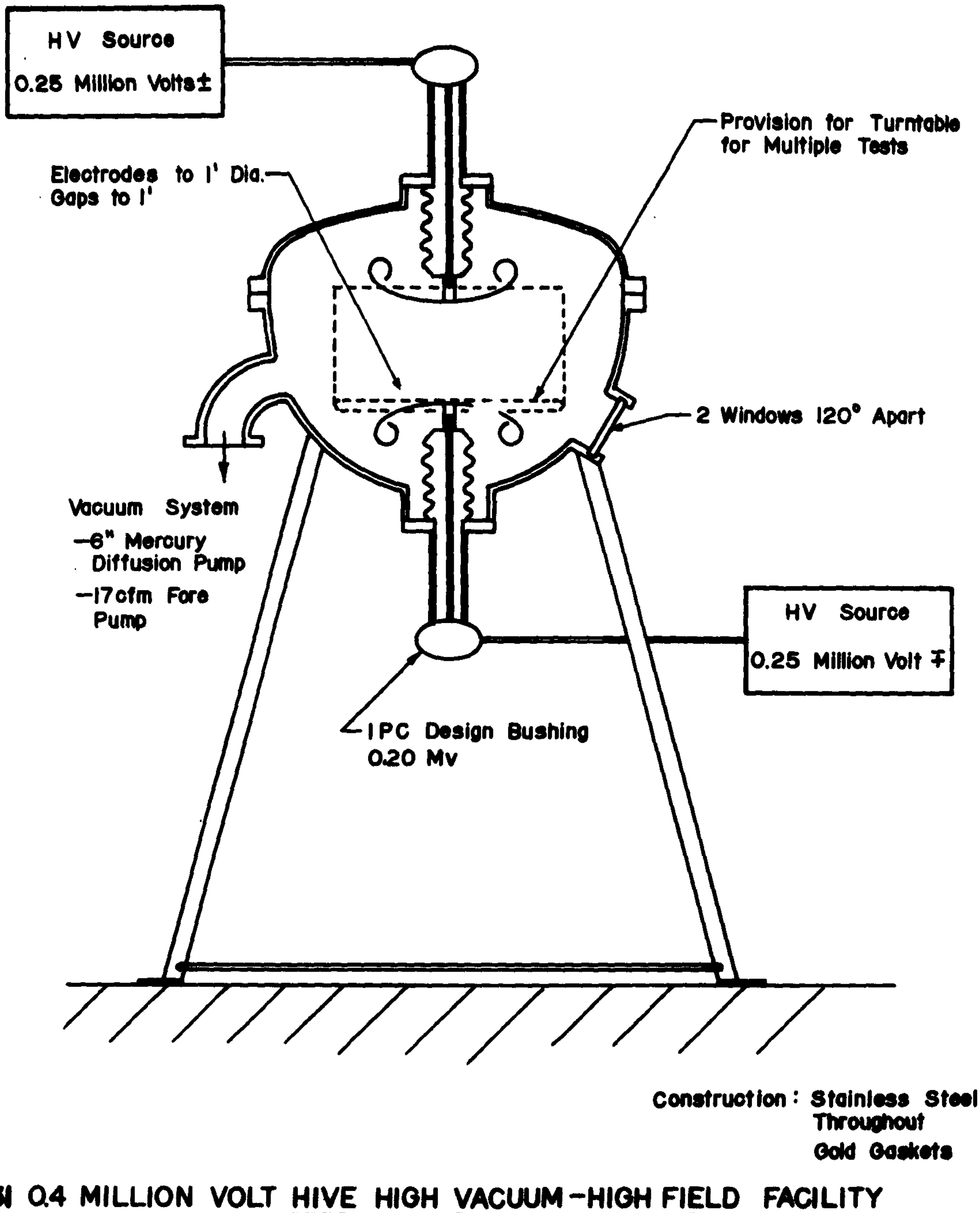


Fig.31 0.4 MILLION VOLT HIVE HIGH VACUUM-HIGH FIELD FACILITY

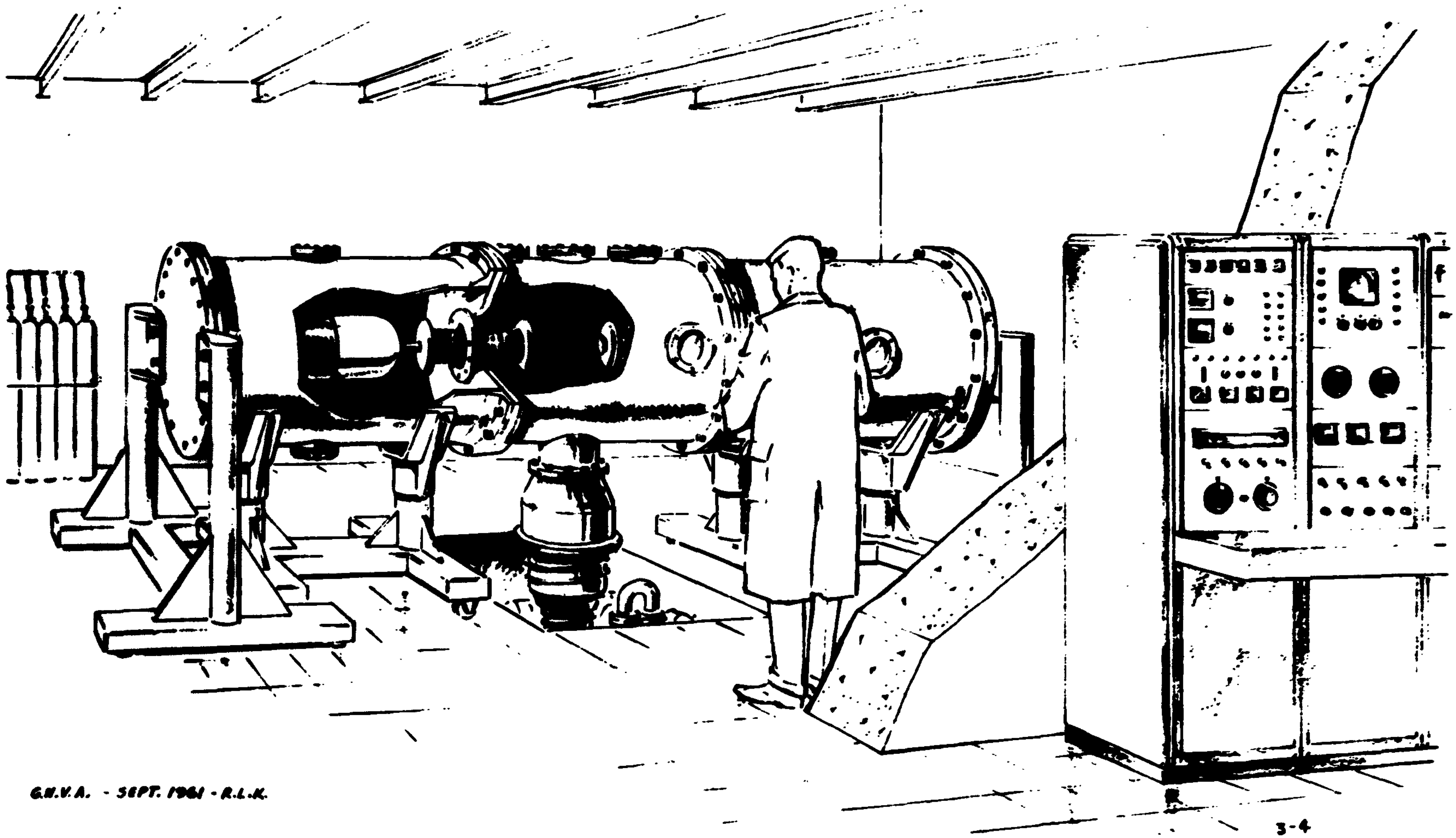


Fig. 32 Cut-a-way View – Miv Facility

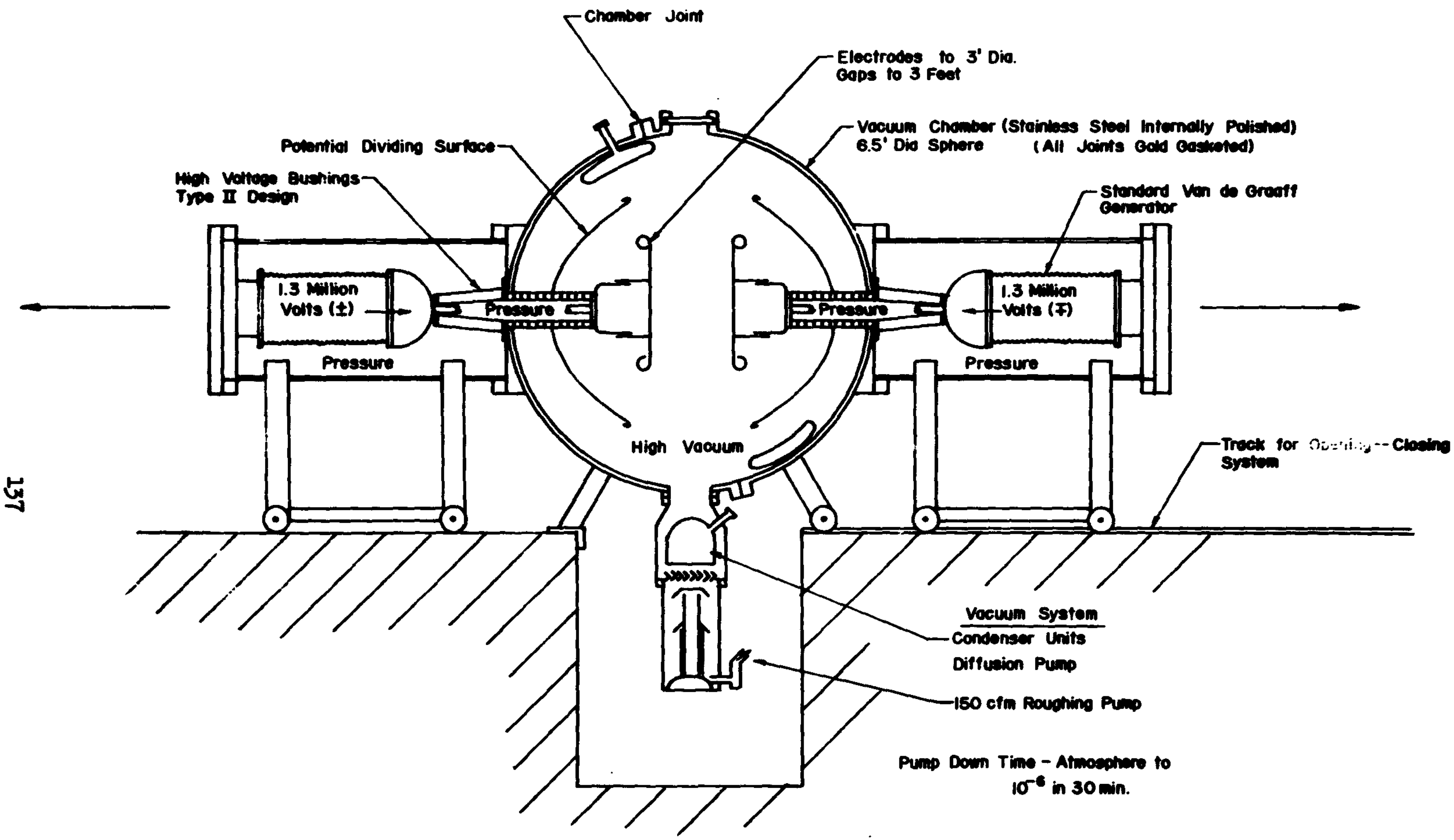


Fig. 33 2 MILLION VOLT FACILITY - WITH PROPOSED MODIFICATIONS

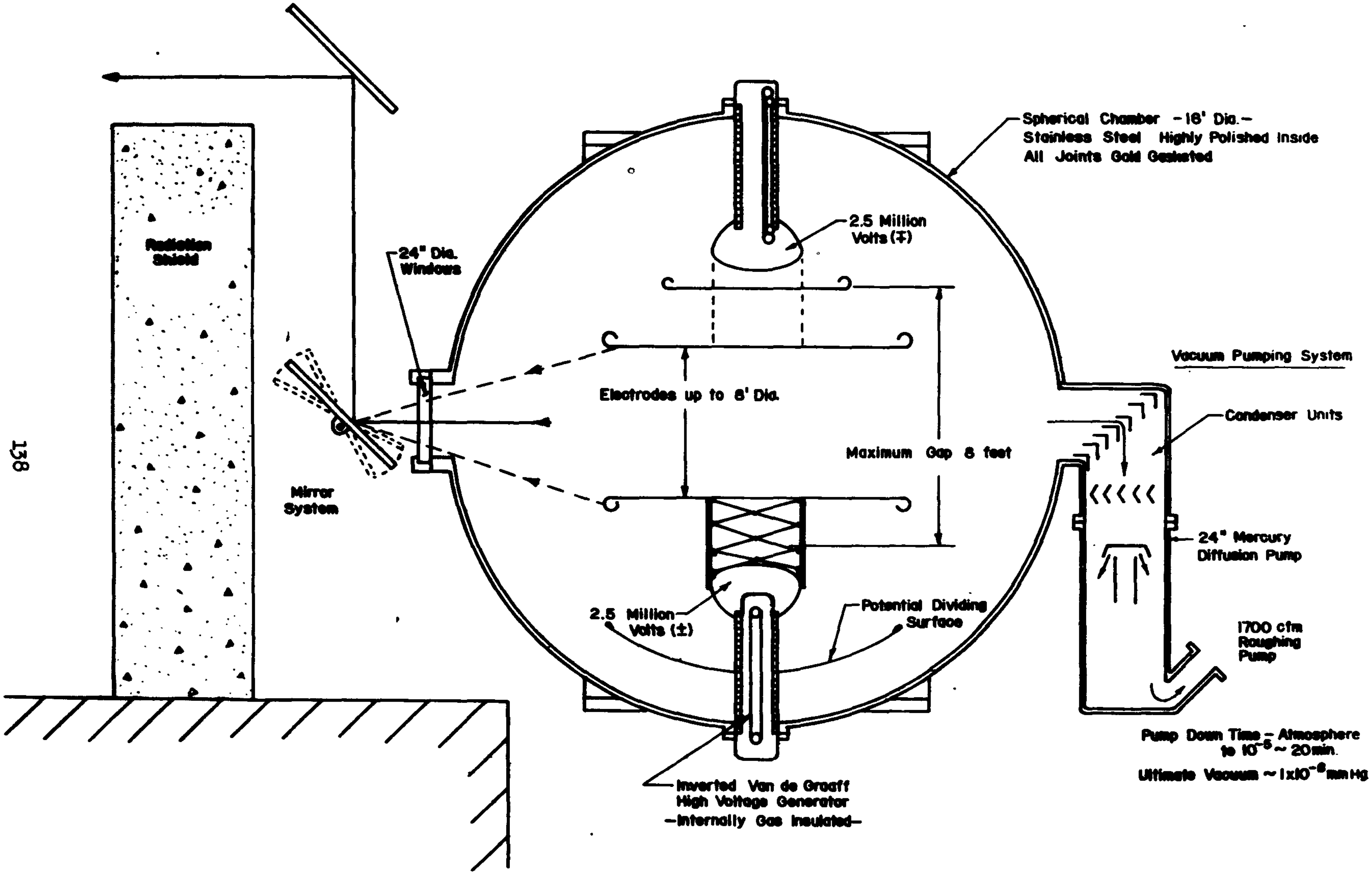


Fig. 34 — 4 MILLION VOLT VACUUM BREAKDOWN FACILITY

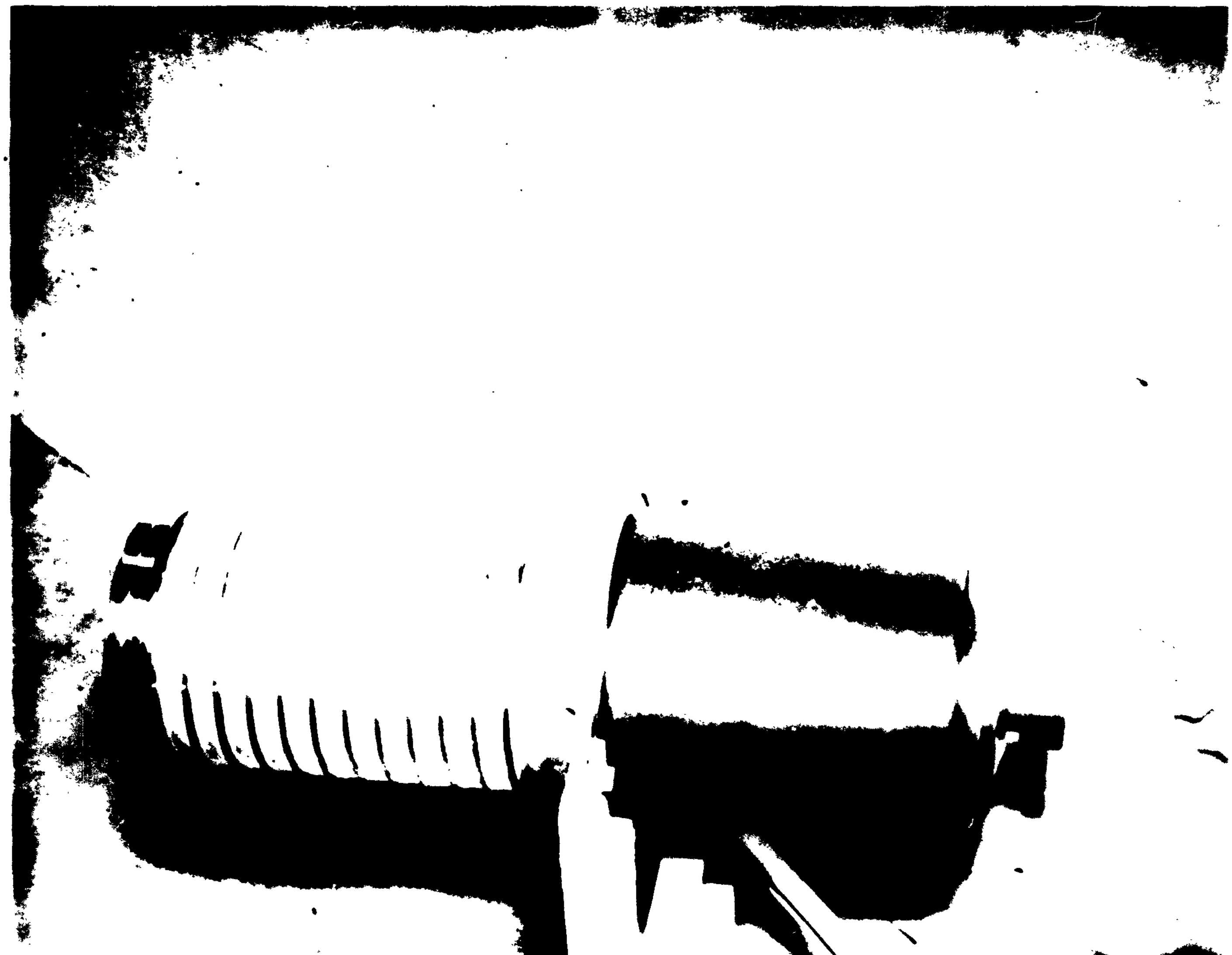


Fig. 35 Type II Bushing

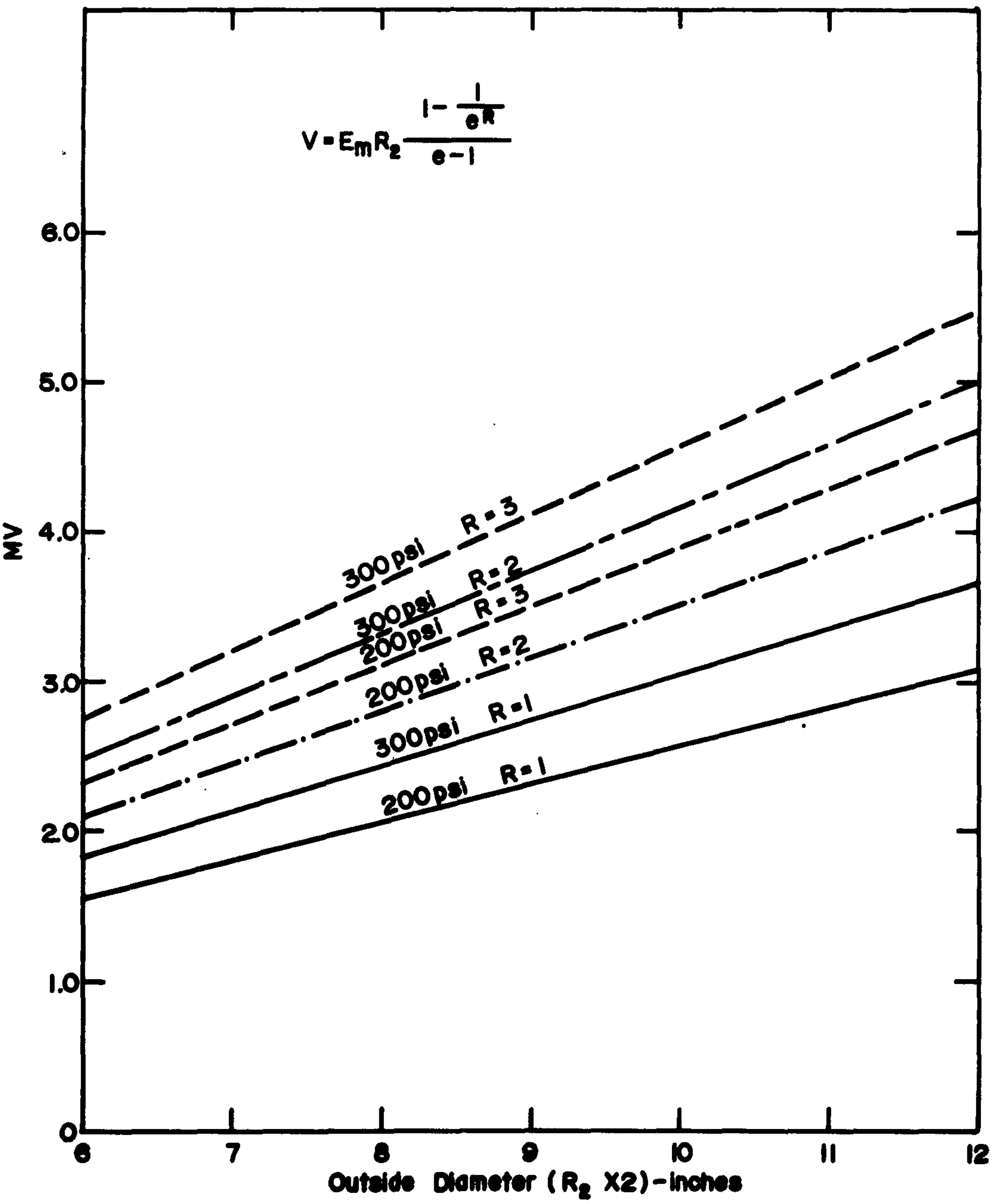


Fig. 38 Voltage Which can be Supported with Cylindrical Geometry Using SF_6. R is the Number of Coaxial Shells. (Field Data E_m, Taken from Philip.)

Because of the rapid set-up time possible in this system, its first purpose in the vacuum breakdown program will be to study special electrode materials. Also, because of its organic free vacuum design (compared with vinyl acetate bonded bushings in the 2 million-volt chamber) it will be used to study the effects of different gases (e.g. H_2, He, N_2, O_2, CO_2, SF_6) at pressures between 10^{-8} and 10^{+3} torr.

MiV-2 Facility

Modifications proposed for the present 2 million-volt facility (MiV-1)* would consist, mainly, of a new spherical vacuum chamber of 7 feet diameter. This large chamber would reduce radically the number of and effects of charged particles crossing the gap between electrodes and the chamber walls. Electrodes of diameters to 3' could be accommodated in lieu of the 1 foot maximum in the present 2.5' diameter system. (See Figs. 33 and 37)

Should this vacuum chamber be obtained and used as an environment for the Type II bushings, their performance should be markedly improved. The insulator column of these voltage-graded bushings, on the vacuum side, may be considered as a series of electrodes -- each affected by other electrodes on either side of it and each affected by the proximity of the large area ground plane electrode -- better known as the "tank." It is the sum total of these electrode effects, paralleled by the vacuum-solid interface surface flashover effects, which act to limit bushing voltage. It is these electrode surfaces, also, which must undergo electrical conditioning each time that voltage is applied, as indicated by a gradual increase in peak voltage as a function of time. In the present million-volt system, the chamber diameter is 76 centimeters (2.5 feet) and the bushing terminal diameter 30 centimeters. This gives a minimum electrode gap of 23 centimeters and a nominal maximum of 0.94 million volts across this gap if $k = 2 \times 10^5$ V-cm$^{-0.5}$. Since k values much above this are unusual, it becomes quite clear that bushing terminal voltage must be limited primarily by wall clearance in this present system. Therefore, if further gains in bushing voltage and, therefore total system voltage, are to be made, they will be gained most rapidly and inexpensively by the installation of an enlarged vacuum chamber.

* (see Fig. 32)

Other improvements to the design would include a large surface area condenser (liquid nitrogen cooled) inside the chamber, potential dividing surfaces to improve bushing performance, quick opening port for change of electrodes, large roughing pump for 15-30 minute pumpdown from atmosphere, "reduced weld" chamber design to avoid leaks, and a track for alignment of chamber halves when opening and closing the system.

Instrumentation improvements planned would include a new optical system for scanning and inspecting electrodes during operation, an RF telemetering system for monitoring current magnitudes and waveforms to the electrodes and for controlling bias voltages to grids with respect to electrode potential, and recording equipment for obtaining better data and partially processing it as it is received (e.g. x-y recorder, analog computer, plots on log-log paper of $V = kd^a$.

4 MV Facility

Results from a long and rather detailed study of the vacuum breakdown program indicate that the most sensible increase in system energy per step is by factors of two. The basic reason for this is that dimensions required for vacuum insulation increase typically with the square of the voltage. Therefore, this facility is proposed as a 16 foot diameter sphere with voltage capability of twice the present system with 4 foot length tank. A spherical chamber design has been chosen from investigations of electric field plots made with various configurations such as: long cylinder-flat ends, long cylinder-hemispherical ends, and sphere. A sphere is the only geometry which permits reasonably large electrode areas with small wall effects. (See Figs. 34 and 38)

Special features of this system have not been clearly established, except that they will include those proposed for MiV-2 and will emphasize the ability for rapid changeover of experiments. In keeping with this, large pumps are planned so that pumpdown time may be held to 30 minutes or less.

Power sources will be of the inverted design and will require a modest development program to attain the required 2.5 million volt rating for both polarities.

8 MV Facility

The general design of an 8 to 10 MV facility would be identical with the predescribed 4 MV facility. However, most dimensions would be increased by a factor of four to account for the non-linearity of voltage-gap relationships. It is expected that inverted high voltage power generators could be extended to two or, at most, three times the length of those required for the 4 MV facility (5 to 7.5 feet for 8 MV facility). These generators would fit in the top and bottom of a sphere approximately 64 feet in diameter $\left[(8 \text{ MV})^2 = 64 \text{ feet}.\right]$

The construction of a vacuum system of this size several years in the future (c. 1965) is not expected to create any great difficulty, in view of the fact that a 38.5 foot diameter chamber was completed during the summer of 1962* which has given excellent vacuum performance. The main problem with this large vacuum system may be connected with obtaining large inorganic fluid vapor diffusion pumps. Most large diffusion pumps used today are oil diffusion which will eventually contaminate the system with oil. High voltage systems give poor performance when contaminated with organics, as displayed by a loss in maximum voltage and an increase in x-radiation levels. Therefore, most high voltage-vacuum insulated devices employ mercury diffusion pumping, with the present size limit being 24" diameter compared with 48" or more for oil diffusion pumps.

We may therefore say that, aside from the expense of a large vacuum system, and the possibility of having to make one's own vacuum pumps, there appears to be no insurmountable problems involved in the construction of an 8 to 10 MV vacuum research facility.

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* Constructed by F. J. Stokes Corporation at King of Prussia, Pennsylvania for use by General Electric Company Space Technology Center.

3.3.4 Allocation of Studies to Existing and Proposed Facilities

It is the purpose of this section to examine the allocation of studies to the existing and proposed facilities for research on vacuum breakdown phenomena. These facilities are:

	Present Voltage Rating	After Modification
(a) HIVE System - high vacuum and high electric field	0.4 MV	up to 1.0 MV
(b) MiV System - million-volt system	1.7 MV	up to 2.5 MV

and the proposed facilities:

(c) 4 MiV System - 4 million-volt system	4.0 MV	
(d) 8 MiV System - 8 million-volt system	8.0 MV	

(a) HIVE System (see Fig. 27)

This system, which has recently become operational, is intended to complement the existing million-volt system. By virtue of its design and voltage rating, HIVE is well suited to a comprehensive study of electrode materials, electrode coatings, and states of finish of electrode surfaces. This is because interelectrode gaps at 400 kv will be about 1 cm: thus plane parallel electrodes about 10 cm in diameter can be used to produce uniform electric fields in the gap. It is then much more economical to carry out a series of tests with electrodes of this size, rather than those of 25 cm diameter normally used in the million-volt facility. Furthermore, the time which elapses whenever electrodes are changed, and the conditioning time for bushings and electrodes, will be shorter than for the other facility.

It is intended that promising electrode materials, coatings and finishes which arise from research in the HIVE system will be examined at higher voltage levels in the million-volt facility. However, studies in the HIVE system can be of a fundamental as well as applied nature, since the system is instrumented to examine pre-breakdown currents between the electrodes and Fowler-Nordheim plots can be made: these may be of extreme significance in understanding the phenomena of breakdown.[82] It is also planned to investigate the effect of ambient pressure and the nature of the ambient gas on the breakdown voltage, and to examine the influence of external circuitry on this voltage and on the waveform of interelectrode discharges.

The high voltage feed-through bushings on the HIVE system can be adapted to allow the introduction of liquid nitrogen to a volume adjacent to the electrodes. These may be cooled by conduction to a low temperature, so that it will be possible to observe the effects of reduced electrode temperature on breakdown.

Finally, it is hoped to use this facility to measure the ratio of charge-to-mass of ions which cross the electrode gap. Such particles would pass through an aperture in an electrode and out into a separately pumped chamber, where they would be deflected and analyzed by a magnetic field as in a mass spectrometer. This experiment may resolve the nature of Cranberg-type clumps which have a postulated role in breakdown.

(b) MiV System (see Fig. 32)

This system has been operational for nearly a year, and during that period it has been used for experiments of two types. In the first place, the design of the pressure-to-vacuum feed-through bushings was new, so that experiments were made to explore the behavior of the bushings and their voltage support capability: this was done by using a variety of field rings, terminations and urethane resistors with the bushings, to determine an optimum geometry. The second type of experiment has been measurement of the breakdown voltage V as a function of electrode separation d at high voltages, for plane parallel electrodes of various materials, for coated electrodes and for electrodes having sphere-to-plane geometry.

It appears that for large electrode separations, the proximity of the vacuum chamber walls may be limiting the voltages which the bushings can support. Replacement of the existing vacuum chamber with a spherical chamber has been discussed in a previous section, but the anticipated experimental program will be the same, whether this modification is accepted or not.

With particular emphasis on the Directed Energy Weapon Program, breakdown tests to determine V as a function of d in hard vacuum will be continued for essentially plane parallel, polished and coated electrodes of 20 cm diameter or larger. It has been suggested by Van de Graaff[83] that voltage-dividing shields surrounding the interelectrode gap would help to provide uniform field conditions between the electrodes, and would render the interelectrode gap less sensitive to bushing inconsistencies: these suggestions will be adopted and results compared with those for electrodes without benefit of shields. Electrode parameters will be determined principally from information gained in HIVE experiments. In addition, this facility is equipped for tests with heated electrodes (in contrast to the HIVE system), for the investigation of breakdown between electrodes having back-biased grids over their surfaces, and for the testing of an initial model of an inverted Van de Graaff generator.

However, it is probable that research into the fundamentals of vacuum breakdown will be as important to the Directed Energy Weapon Program, and the million-volt system is suitable for this. Such an investigation includes experiments with uniform, shielded gaps described above, with instrumentation to determine pre-breakdown currents and the current density distribution over the electrode surface, and the use of phosphor-covered electrodes for visual observation. The contribution of photoelectric, thermionic and field emission to breakdown must be considered, and can be examined experimentally in the million-volt system. It is also planned to observe the effect of introducing radio-active isotopes to the proximity of electrodes, since this technique allows the bombardment of electrode surfaces by controlled amounts of ions, electrons or high energy photons.

[redacted]

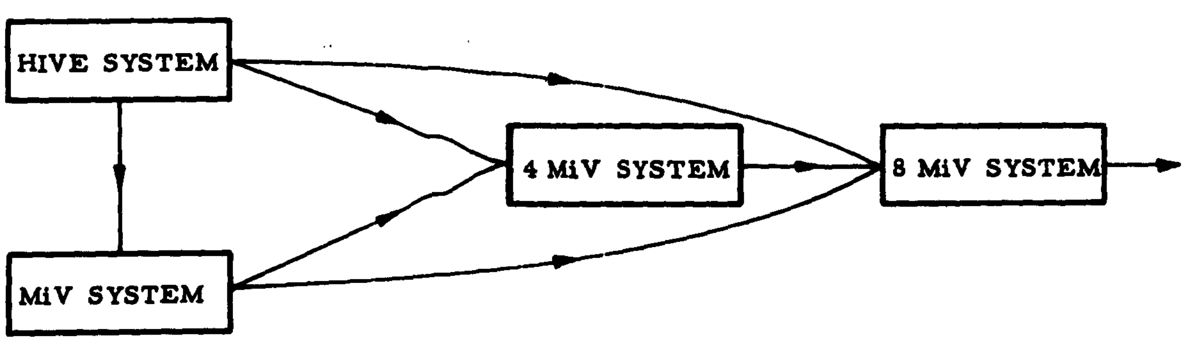
Finally, those fundamental studies which are made with the HIVE system -- investigation of the ambient pressure effect, etc. -- can be performed in the million-volt system at higher voltages and larger electrode separations.

(c) 4 Million Volt System (see Fig. 37)

It is envisaged that fabrication of this system, and development of the power supplies for it, will take 12 months. On completion of this phase, it is anticipated that an examination of breakdown voltages as a function of inter-electrode distance will be made for promising electrode materials and coatings, with the object of ascertaining whether an immediate breakthrough in the support of high voltages in vacuum is possible. Experimental and theoretical studies in connection with the HIVE and MiV systems will be used in determining the nature of these experiments, but it is expected that they will follow closely the type of experiments already performed in these chambers at lower total voltages.

(d) 8 Million Volt System (see Fig. 38)

The initial experimental program to be carried out in this system will be the same as that for the 4 MiV system outlined above. It is felt that a study at these voltage levels, which emphasizes both the fundamental and applied aspects of the problem, is the best approach to the high voltage insulation and generation problems posed by the Directed Energy Weapon Program. Full interchange of experimental results between the systems is planned, although it is expected that information will primarily follow the directions shown below.



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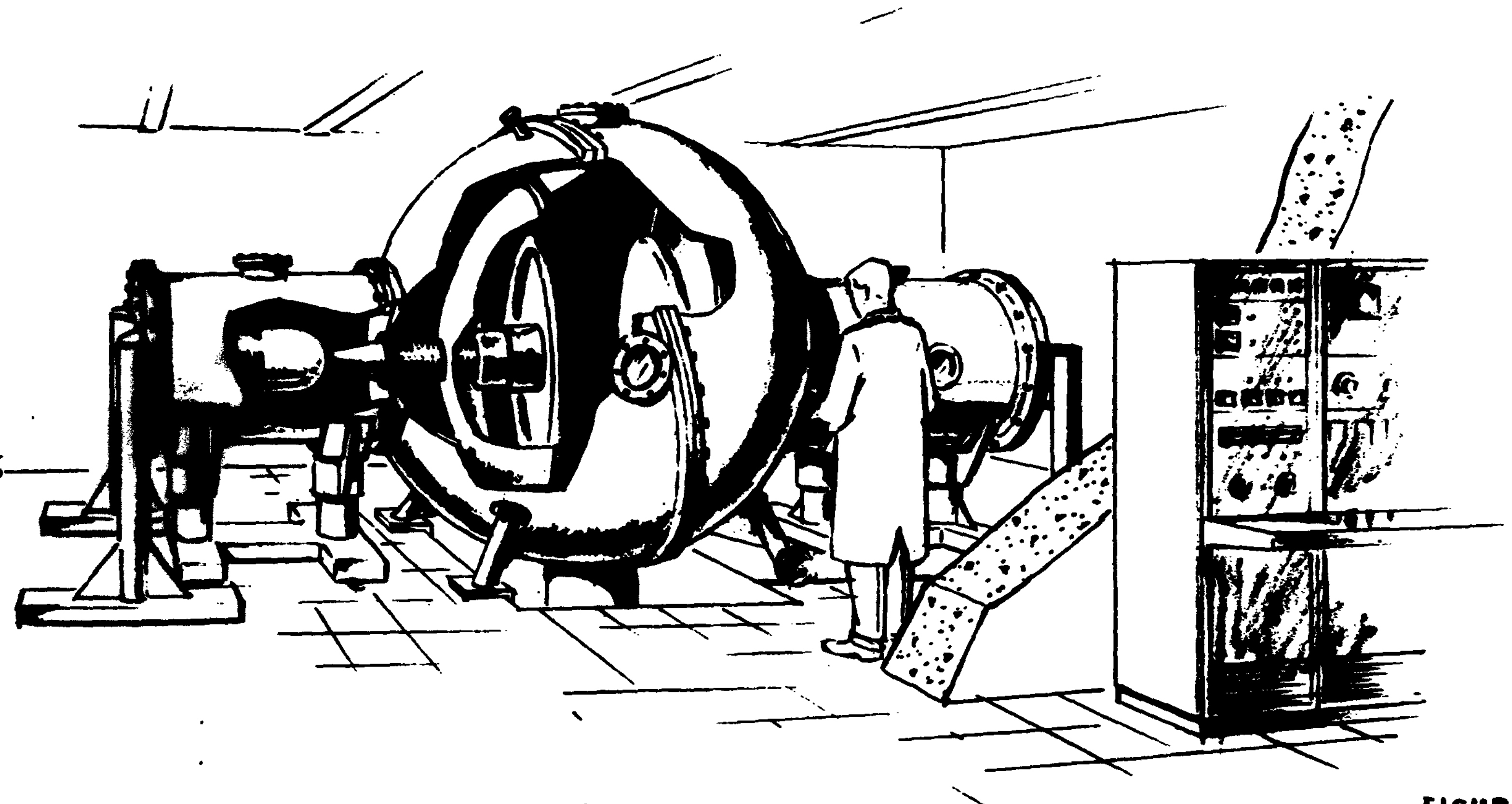

2.5 MV VACUUM INSULATION FACILITY

ION PHYSICS CORPORATION
BURLINGTON, MASS.

FIGURE 37

FEBRUARY 1963 - R.L.K.

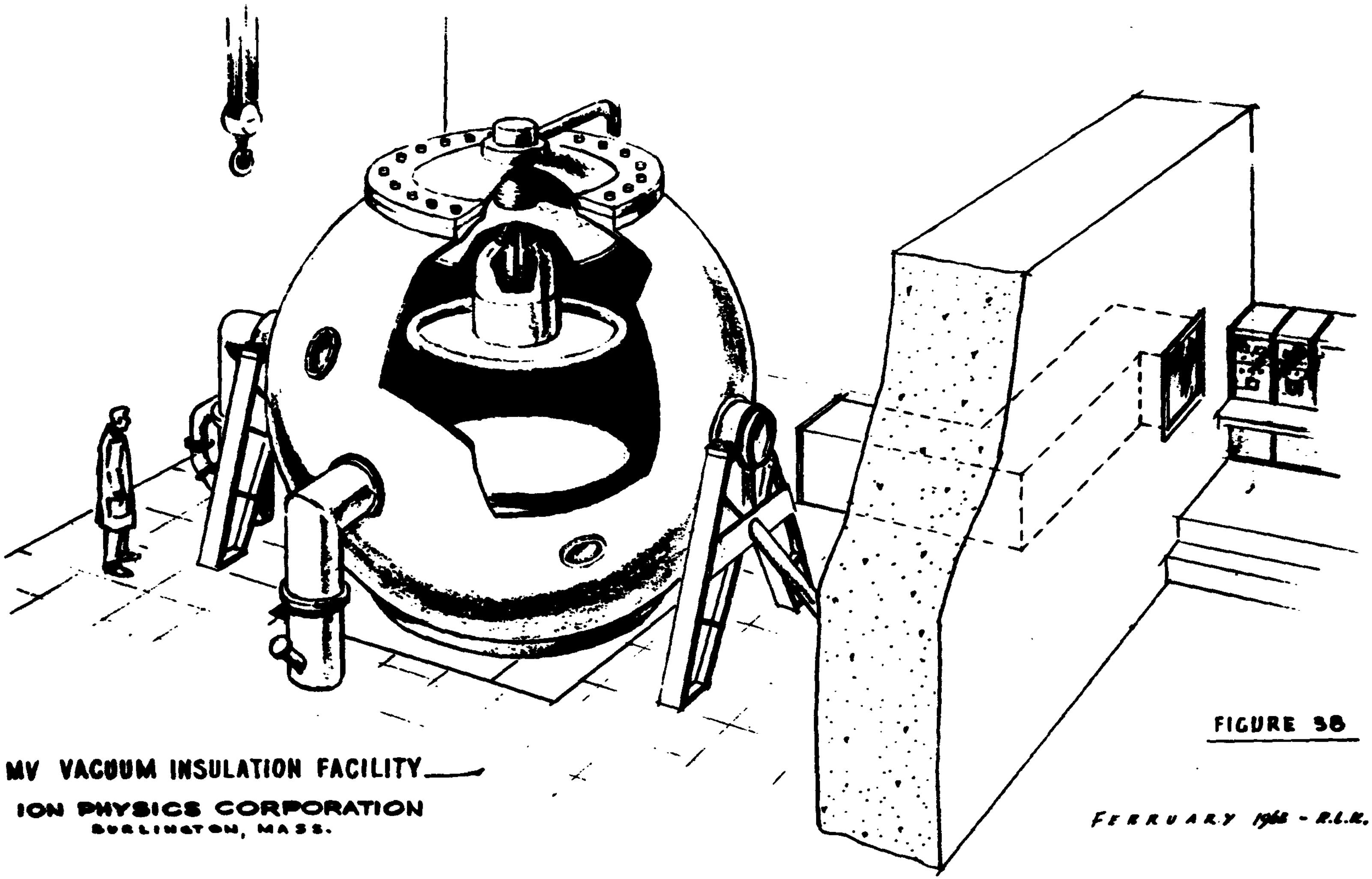

FIGURE 38

4 MV VACUUM INSULATION FACILITY

ION PHYSICS CORPORATION
BURLINGTON, MASS.

FEBRUARY 1968 - R.L.K.

[redacted]

3.4 GROWTH PLAN FOR FACILITIES TO SOLVE THE PROBLEMS OF HIGH VOLTAGE INSULATION IN SPACE

A proper treatment of the high voltage vacuum insulation problem would create physical equations that could be used for solution of any voltage-current-gap-geometry situation. Such equations could conceivably allow calculation of material performance (Cranberg k values) from data such as atomic constituents, crystalline structure, electrical and thermal conductivity, specific heat, yield strength vs. temperature curves, ductility, work function, etc. The background for such formulae must therefore contain data from a wide voltage and gap range and also a variety of geometrical configurations. The basic idea of a particulate beam directed energy weapon implies high energy beams and therefore high total voltage acceleration devices. It is therefore necessary that one study electrical breakdown in vacuum at very high voltages and at voltages at least equal to the maximum voltage steps which will be designed into the final particle accelerator.

With this high voltage goal in mind, a growth plan has been developed for attainment of 8 to 10 million volts across single gaps in vacuum. The figure of 10 million, however, is based on extrapolation from presently available data which only reaches 1.7 million volts. Therefore, it must be understood that the maximum voltage of each proposed facility may only be determined experimentally. The proposed growth plan is outlined on Fig. 39 which also has inset the present and projected potentials available in vacuum according to the plan. The inset also includes the approximate dimensions of the vacuum chambers required to attain these potentials according to extrapolation of the best available data.

The one to two million volt facility (Fig. 25) was the first system developed by IPC. Experimentally, the power sources have proven capable of 2.7 million volts potential difference. The combination of both power sources, Type I bushings and present vacuum chamber have achieved only 1.7 million volts potential difference. As previously explained, it is now realized that voltages much higher than 2.0 million will not be obtained in this chamber, and yet only because of its small sise. The first step in facility growth should therefore be the installation of a larger vacuum chamber on this facility, thereby raising its working voltage to the 2.0 MV region and its maximum to approximately 2.6 million

[redacted]

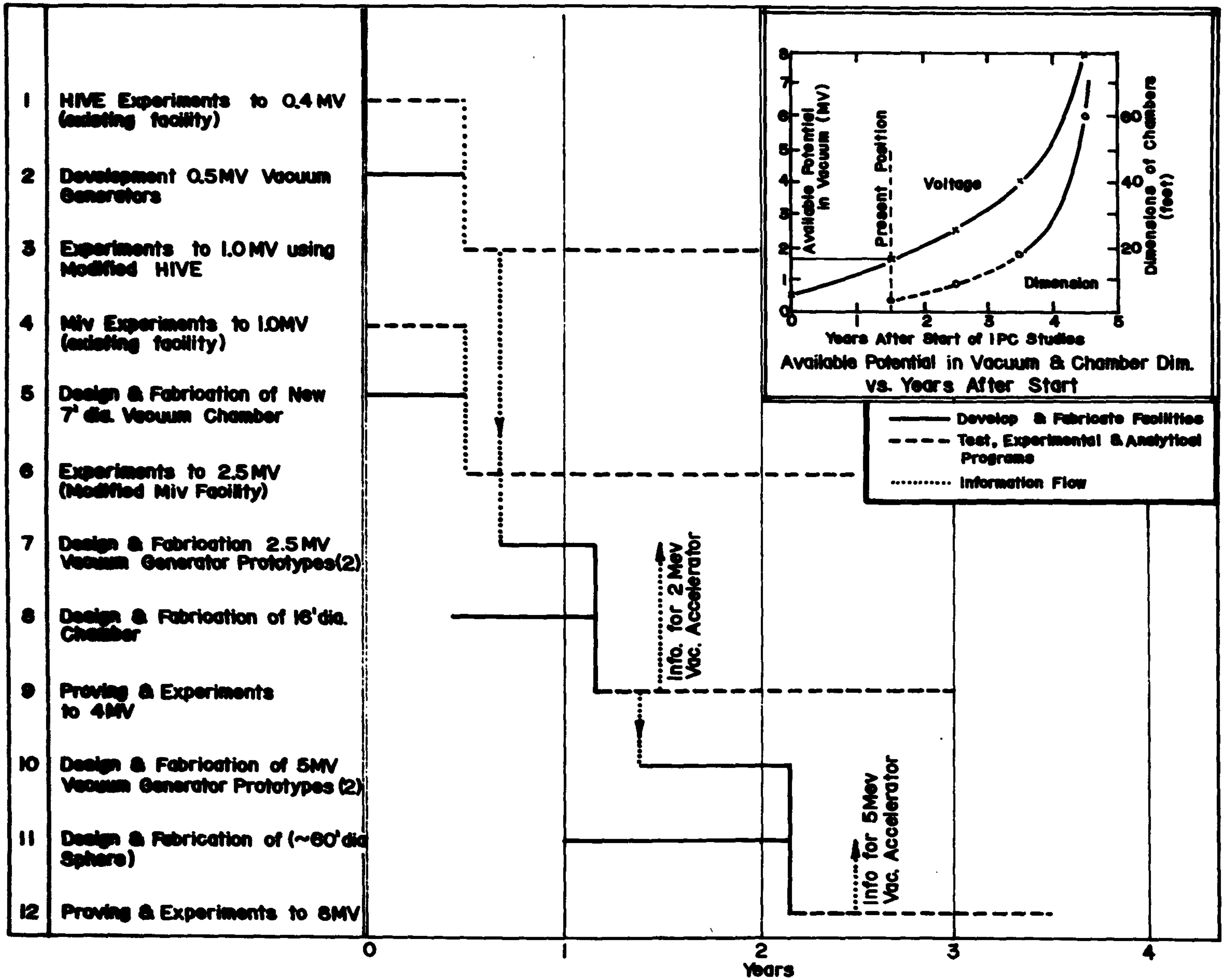

Fig. 39 Growth Plan— High Voltage Insulation Facilities & Studies

volts. (Fig. 39, line 5). It seems advisable, in view of the small expense and the large gains to be reaped by this step, that it be undertaken in the immediate future.

The 0.4 MV HIVE facility shown in Fig. 27 was the second vacuum breakdown system to be developed at IPC. Individually, the bushings and power supplies of this chamber in the initial test stages have reached a potential difference of 0.38 MV. There is every indication, however, that this chamber would be suitable for approximately 1.0 MV total if suitable power were available. The power source which seems most applicable is the inverted generator, and possibly the inverted Van de Graaff concept. Such a power source could be developed in a small package to fit the HIVE, with a design voltage of around 0.5 MV. If it proves satisfactory, fabrication of a second unit would give a total of 1.0 MV for the system. Therefore, the second step in facility growth is envisaged as development of prototype inverted power generators and the incorporation of these generators in a vacuum breakdown facility. (Fig. 39, lines 2 and 3) Further advantages from this plan are that working experience with the inverted supply could be compared with past experiences with external supplies plus bushings in the two million volt facility.

The third stage planned in facility growth is the development of power sources for a 4 million volt facility. (Fig. 39, line 7) Each source should have a nominal rating of approximately 2.5 MV positive or negative. This voltage is within the limits of operation for the enlarged chamber proposed for the 2 MV facility. Therefore, by proper flange and port design, the 2.5 MV inverted power generator may be built and tested before construction is begun on the total 4 MV facility with 16 foot diameter chamber. This generator, externally insulated by vacuum, is almost immediately applicable as the supply for a vacuum insulated (space borne) accelerator, and this sub program mates with the accelerator programs as shown on Figs. 22 and 39.

Following successful development of a 2.5 MV power generator, the fifth step in facility growth would be actual fabrication and assembly of the 4 MV facility including fabrication of a second 2.5 MV generator.

It is felt that considerable experimental research time and effort might be oriented around the 4 MV machine and that its abilities be pushed to the utmost before much thought is put toward higher energy levels. It is conceivable that high voltage-vacuum studies will be more or less completed at the 4 to 5 million volt level. The attainment of higher energies across single gaps could then prove to be unnecessary.

However, if higher energy levels are required, development of inverted power sources would be extended to the 5 MV level, using the 16 foot diameter facility for test purposes. (Fig. 39, line 10) Fabrication of a second 5 MV supply would follow, simultaneously with construction of a suitable vacuum chamber, radiation shielding, and instrumentation for performance of experiments at the 10 MV level.

The estimated funding requirements to carry out this program are included on Fig. 24 a, b and c.

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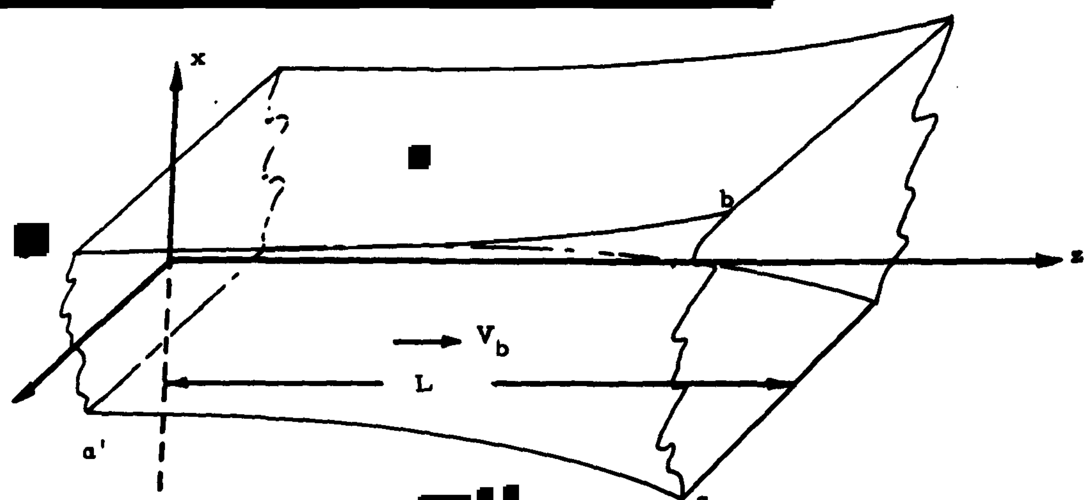

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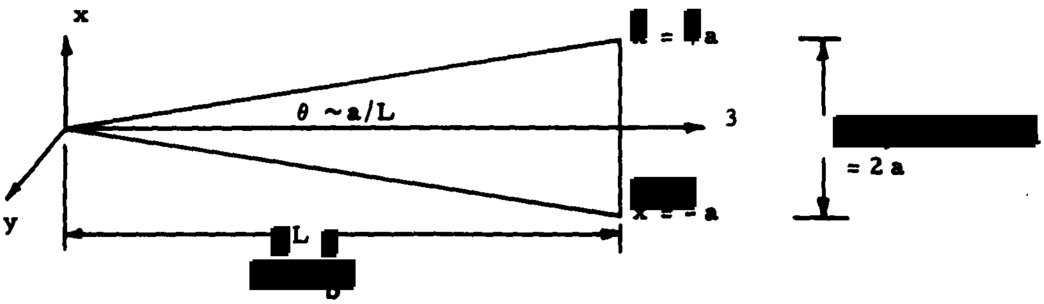

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$$\xi \text{ [redacted] } \sqrt{\beta} \text{ [redacted] } t) \text{ [redacted]}$$

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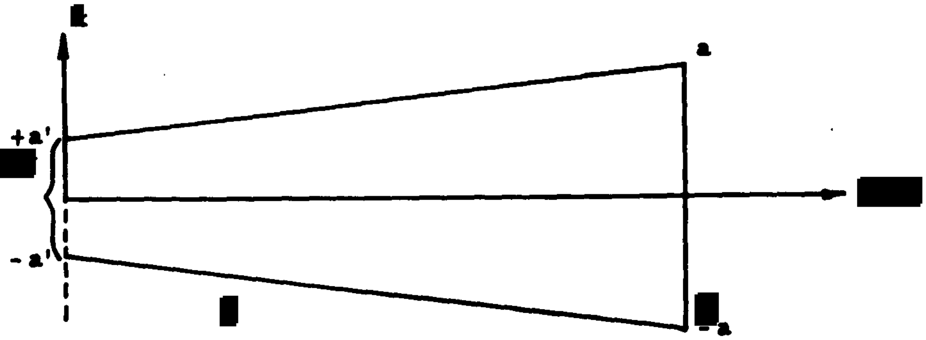

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I [redacted]) [redacted]

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I_p [redacted] $a'(\beta/\pi)$ [redacted] $^{1/2} \int^{+a'}$ [redacted] $x \int^{\beta^{1/2}(a-x)/t}$ [redacted] $\beta^{1/2}$ [redacted] t [redacted] ^{2} [redacted]

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APPENDIX II

CHARGE FLOW DOWN AN ACCELERATOR TUBE AND THE IMPLICATION TO POTENTIAL GRADING

To allow a high current beam to pass effectively down an accelerator tube it is essential that the passage of the beam should not significantly influence the accelerating gradient down the column. The design of accelerator tubes and associated parts to maintain gradient with high currents is designated "beam stiffening." This loss of gradient can either be by influence charge movements or by direct interception of a fraction of the beam.

A. THE EFFECT OF INFLUENCE CHARGE FLOW

To simplify the treatment, certain assumptions are made concerning the equivalent circuit of the generator during the pulse discharge, and also concerning the charge density of the beam. The circuit which is assumed is shown in Fig. (II- 1). Capacitance C_{AG} is large since it contains several times the stored energy to be extracted by the beam. In the specific case of interest C_{AG} is 10, 000 μμf. The interelectrode capacitances C_{SB}, C_{SC}, etc., are assumed equal, which is reasonably correct even for an accelerator without special capacitances added for beam stiffening, as can be seen from the following table, which shows measurements made on a 3 MV accelerator.

Capacitances Between Adjacent Potential Rings on a 3 Mev Van de Graff Column

Rings Number	1/2	10/11	24/25	34/35	46/47	62/63
Capacitance (μμf)	261	239	235	254	237	240

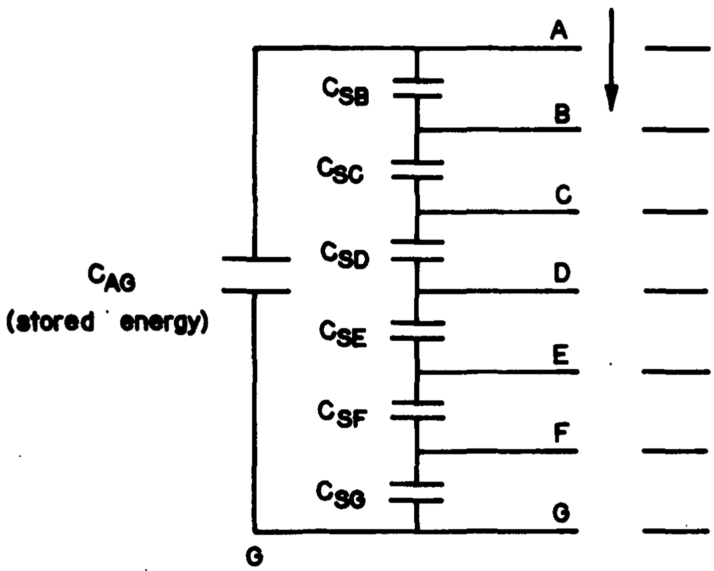

Fig. II-1 Equivalent Circuit-Accelerator Tube System

These measurements were made with the tank removed, but bearing in mind that the capacitance of the relatively large terminal to ground (tank) is perhaps 150μμf, these values would not be appreciably changed by the presence of the tank.

Consider a small packet of charge q_p at the front of the beam. As it moves from region A to region B there is a corresponding charge movement in the external circuit. Part of the charge takes the path A to B, discharging C_{SB}, and the remainder path AGB, discharging C_{AG} and charging C_{BG}. The flow through the two paths is shared directly as the capacitance of the two routes.

The voltage drop Δv associated with the flow q_p is $\Delta v = \frac{q_p}{C}$ where (1)

$C = C_{SB} + \frac{C_{AG} C_S (n-1)^{-1}}{C_{AG} + C_S (n-1)^{-1}}$ and $C_{SB} = C_{SC} = C_{SD} \ldots = C_S$; there are n sections in the tube.

i. e.

$$C = C_S + \frac{C_{AG} C_S}{(n-1) C_{AG} + C_S} \tag{2}$$

$$= \frac{C_S(nC_{AG} + C_S)}{(n-1) C_{AG} + C_S} \tag{3}$$

$$\text{so } \Delta v = q_p \left[\frac{(n-1) C_{AG} + C_S}{C_S (nC_{AG} + C_S)} \right] \tag{4}$$

In moving from B to C this charge q_p causes the same drop in voltage Δv across C_{SC} and so on. The increase in voltage across, for example, C_{SB} when gap BC is being traversed is $\Delta v'$ where,

$$\Delta v' = \Delta v \times \frac{C_{AG} C_S}{(n-1) C_{AG} + C_S} \frac{1}{C_S} = \frac{C_{AG} \Delta v}{(n-1) C_{AG} + C_S} \tag{5}$$

and the decrease in voltage across C_{AG} when, for example, gap BC is being traversed, is $\Delta v''$ where,

$$\Delta v'' = \frac{\Delta v \; C_{AG} \; C_S}{(n-1) C_{AG} + C_S} \qquad \frac{1}{C_{AG}} = \frac{C_S \, \Delta v}{(n-1) \, C_{AG} + C_S} \tag{6}$$

For the complete traverse of the accelerator tube, the total drop in voltage across C_{AG} due to q_p is

$$n\Delta v'' = \frac{n \, q_p}{n \, C_{AG} + C_S} \rightarrow \frac{q_p}{C_{AG}} \tag{7}$$

The net change in voltage (Δv_n) across any C_S for a complete traverse of the accelerator tube by q_p is

$$\Delta v_n = \Delta v + (n-1) \, \Delta v'$$

$$= - \frac{q_p}{nC_{AG} + C_S} \rightarrow -\frac{q_p}{nC_{AG}} \tag{8}$$

It follows from these considerations that the first interelectrode gap suffers the greatest drop in gradient due to influence charge movements, and that after the tube is full of charge there is no further drop in the gradient of that gap, except insofar as the potential of C_{AG} falls.

The maximum drop in potential of C_{SB} is essentially when the tube is just full of charge. Each element of charge in the tube will have subtracted from C_{SB} a net amount of charge depending on the position of that element of charge in the tube. This is illustrated in Fig. II-2 where the charge loss in the capacitance across the first interelectrode gap ($0 \rightarrow x_1$) is plotted against the position of charge q_p producing that loss.

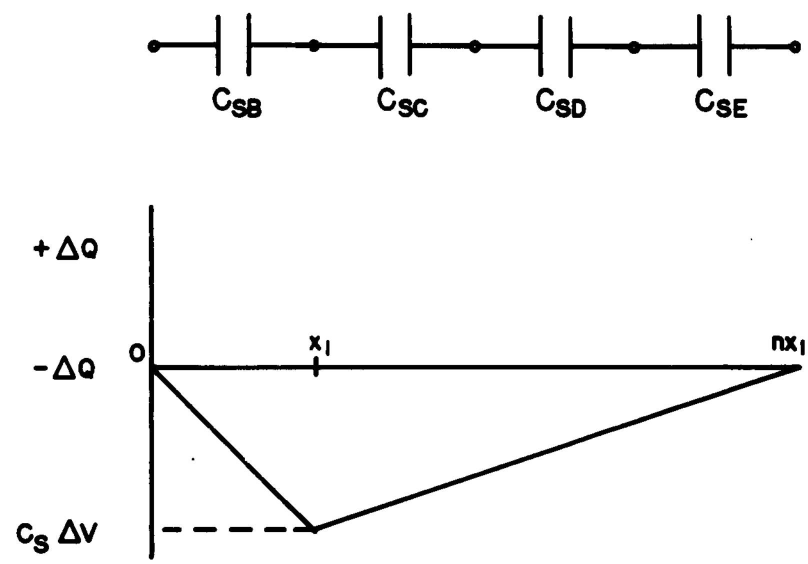

Fig. II-2 Charge Displacement on First Interelectrode Capacitance for 4 Gap Tube. V Position of Charge q_p Causing Displacement

$$C_S \Delta V = q_p \frac{[(n-1) C_{AG} + C_S]}{C_S (n C_{AG} + C_S)}$$

The linear charge density distribution is obviously significant to the determination of the total ΔQ (ΔQ_T) due to all the charge in the tube. Let the linear charge density distribution be $N_\ell = f(x)$. It is required to determine the change of potential across the first interelectrode gap due to all the charge in the beam. From Fig. (II-2) it can be seen that ΔQ, due to any charge between the first interelectrode gap, is a function of the position of that charge, such that

$$\Delta Q_1 = \frac{x}{x_1} \quad C_S \Delta v \quad 0 < x < x_1 \tag{9}$$

and in the remainder of the tube,

$$\Delta Q_2 = \frac{nx_1 - x}{x_1(n-1)} \quad C_S \Delta v \qquad x_1 < x < nx_1 \tag{10}$$

Considering the element of length δx and the linear charge density (N_ℓ) then from expression (4)

$$\Delta Q_1 = \frac{x}{x_1} \quad N_\ell \quad \frac{\delta x \left[(n-1) CAG + C_S \right]}{nC_{AG} + C_S} \tag{11}$$

and

$$\Delta Q_2 = \frac{nx_1 - x}{x_1(n-1)} \quad N_\ell \quad \frac{\delta x \left[(n-1) C_{AG} + C_S \right]}{nC_{AG} + C_S} \tag{12}$$

The total loss of charge of the first interelectrode capacitance is then given by:

$$\Delta Q_T = \int^{x_1} \left[\frac{(n-1) C_{AG} + C_S}{nC_{AG} + C_S} \right] . \frac{x}{x_1} \quad N_\ell \quad dx$$

$$+ \int_{x_1}^{nx_1} \left[\frac{(n-1) C_{AG} + C_S}{nC_{AG} + C_S} \right] . \frac{nx_1 - x}{x_1(n-1)} . N_\ell \, dx \tag{13}$$

Constant Velocity Beam: Consider the case of a beam moving with constant velocity (v) through the tube such that $\frac{dq}{dt} = I$. This is approximately the case for an energetic electron beam ($v \approx c$). Then $N_\ell = \frac{I}{v}$ is constant.

$$\Delta Q_T = \left[\frac{(n-1)\, C_{AG} + C_S}{(nC_{AG} + C_S)\, x_1} \right] \cdot \frac{I}{v} \left[\int_0^{x_1} x\, dx + \int_{x_1}^{nx_1} \frac{(nx_1 - x)\, dx}{n-1} \right]$$

$$= \left[\frac{(n-1)\, C_{AG} + C_S}{(nC_{AG} + C_S)} \right] \cdot \frac{I}{v} \, \frac{nx_1}{2} \qquad (14)$$

For the case in mind, $C_{AG} = 10,000$ μμf, $C_S = 250$ μμf, $n = 40$, $I = 100$ amperes, $v = c = 3 \times 10^8$ M/S, $x_1 = 2.5 \times 10^{-2}$ M and $\Delta Q_T = 1.63 \times 10^{-7}$ C. The drop in potential across the first gap is $\frac{\Delta Q_T}{C_S} = 650$ volts. Compared with gap potential of 50 kv, this can be neglected.

Constant Mass Beam, Variable Velocity: Consider the case of a beam being accelerated by a constant gradient (E_t) but neglect relativity effects (low energy ion beam). With an injection energy V, the velocity of the particles in the beam (v) is given by:

$$v = \sqrt{\frac{2eV}{m} \quad \frac{2eE_t x}{m}} \qquad (15)$$

and

$$N_\ell = \frac{I}{v} = \frac{I}{\sqrt{\frac{2e}{m}\,(V + E_t x)}} \qquad (16)$$

By substituting (16) in (13) and integrating

$$\Delta Q_T = \frac{4}{3} \frac{I}{E_t^2 \sqrt{\frac{2e}{m}}} \left[\frac{(n-1)\, C_{AG} + C_S}{(n\, C_{AG} + C_S)} \right] \frac{1}{(n-1)x_1}$$

$$\times \left[V\sqrt{V}\,(n-1) + \sqrt{V + E_t x_1}\,(-E_t n x_1 - nV) + \sqrt{V + E_t n x_1}\,(E_t n x_1 + V) \right] \qquad (17)$$

For the case in mind, C_{AG} = 10,000 μμf, C_S = 250 μμf, n = 40, I = 1 ampere, V = 100 kv (say), E_t = 20 kv/cm, $x_1 = 2.5 \times 10^{-2}$M, $e = 1.6 \times 10^{-19}$C, $m = 1.67 \times 10^{-27}$ kg (proton).

Substituting in (17) this gives $\Delta Q_T = 1.6 \times 10^{-7}$ C and the drop in potential across the first gap $\frac{\Delta Q_T}{C_S}$ = 650 volts. Compared with the gap potential, this drop is not significant, but is within one order of being so. A lower interelectrode capacitance, a lower accelerating gradient, a higher current or a greater particle mass than that assumed could make the fall in gradient due to influence charge effects significant.

In conclusion, it should be noted that the integrated changes of charge of all the interelectrode capacitances of the tube due to the presence of the beam is zero. This can be confirmed by referring to Fig. (II- 3) which shows, for a 4-gap tube, the effect of an element of charge q_p on the charge displacement in each interelectrode capacitance plotted against the position of q_p in the tube. For example, q_p at ordinate x is associated with the following displacement charges.

capacitance	C_{SB} ——	$-y_2 = -3y_1$
"	C_{SC} ——	$+y_1$
"	C_{SD} ——	$+y_1$
"	C_{SE} ——	$+y_1$

It can be seen that the total displacement charge is zero and this is the case for all the charges in the tube irrespective of linear charge distribution.

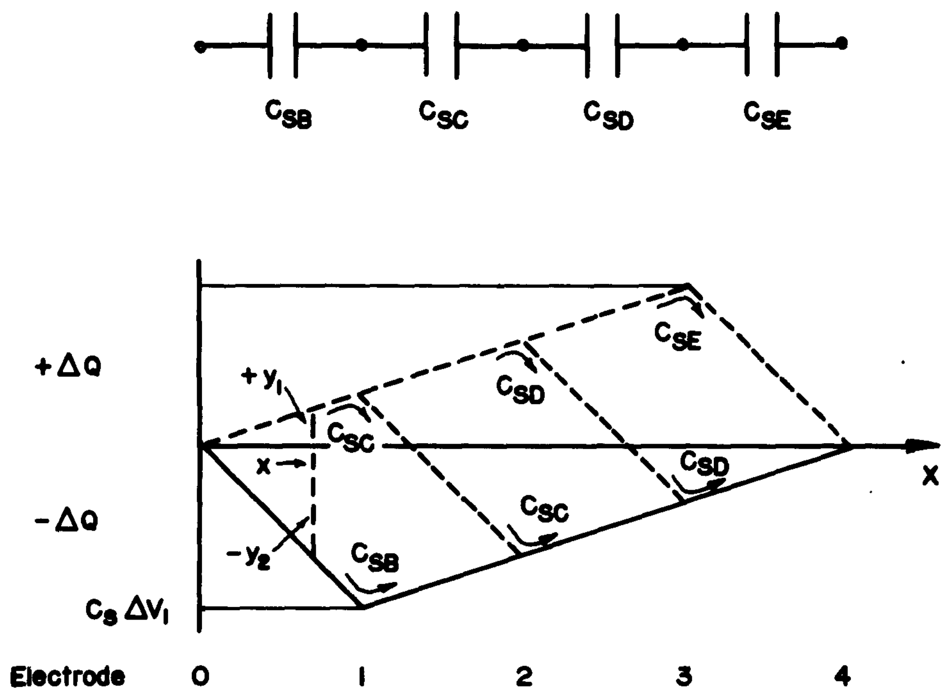

Fig. II-3 Charge Displacement on Each Capacitance V Position of Charge q_p Causing Displacement

$$C_S \Delta V_1 \doteq q_p \frac{\left[(n-1) C_{AG} + C_S\right]}{C_S(nC_{AG}+C_S)}$$

Curve C_{SB} — effect on capacitance C_{SB}

Curve C_{SC} — effect on capacitance C_{SC}

Curve C_{SD} — effect on capacitance C_{SD}

Curve C_{SE} — effect on capacitance C_{SE}

B. DIRECT INTERCEPTION

The effect of direct charge interception by the electrodes on the voltage distribution is cumulative over the duration of the pulse. The fraction of the beam which will be intercepted by any given electrode is related to beam optics, scattering, etc., and will not be discussed here beyond assuming a percentage interception. It is quite possible that leakage 'conduction' in the tube would be more important in losing charge than beam interception.

The charge in the beam pulse is 10^{-3} C. With an interelectrode capacitance of 250 $\mu\mu$f and interception of 0.1% of the beam at the first electrode there would be a potential drop of 4 kv across the first gap, or a change of gradient of 8%, which is significant. It would seem advisable then to increase the interelectrode capacitance to a value which should be determined by experiment, starting at perhaps 5,000 $\mu\mu$f and decreasing the value until deleterious effects are noted.

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