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DEVELOPMENT AND APPLICATION OF A 1-MV 1-MA MYLAR DIELECTRIC PULSED ELECTRON ACCELERATOR AND CONCEPTS FOR HIGHER ENERGY MODULAR GENERATOR SYSTEMS

PIIR-26-71

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Presented at
Eleventh Symposium on Electron,
Ion, and Laser Beam Technology,
May 1971, Boulder, Colorado

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ILLUSTRATIONS

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CONTENTS

SECTION 1

INTRODUCTION

Pulsed relativistic electron beams have been used over the last five years for the following applications:

a. pulsed bremsstrahlung generation
b. ion acceleration
c. high-energy density equation-of-state studies
d. plasma heating

In each of these areas it has become apparent that requirements for higher output currents from pulsed electron beam generators necessitate a modularization of machine components and the combination of outputs from separate generators. The modular approach has already been employed in the generators, as illustrated in this paper. The next order of magnitude increase in output current will require the transport and combination of electron beams themselves. The objective of this paper is to describe this modularization and recombination. Section 2 will describe the manner in which eight separate Mylar dielectric Blumleins have been combined to obtain 1.0-MA output current from a single diode. The following section will present alternative schemes for beam transport and combination of beams from several such diodes. The advantages and limitations of each of these techniques will be described.*

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* The work described was supported in part by the Defense Atomic Support Agency.

SECTION 2
PULSER DESCRIPTION

The pulsed electron accelerator constructed for these experiments is shown in Figure 1. Design output levels for this machine (SNARK) were peak voltage and current levels of 1 MV and 1 MA. Since the maximum linear current density from a Mylar stripline into a matched load is 330 kA/m (at the peak operational stress of 1.5 MV/cm) it was decided to use two modules, each containing two parallel lines with 1.35-meter-wide copper electrodes, in order to operate at more conservative electric field levels. Each module could therefore safely provide 500 kA at operating fields of 0.85 MV/cm. Another factor in the design of the pulser was the desire to limit the absolute voltage on a single Blumlein to a value $\leqslant$ 500 kV (on the basis of previous experiments with high voltage Mylar striplines, Reference 1). Thus, in order to achieve the output voltage of 1 MV, two additional lines were placed in series with the above two parallel lines in each module. A schematic of the generator circuit is shown in Figure 2. Each Blumlein has an impedance of 1.1 ohm, giving a module impedance for the series parallel combination of 1.1 ohm. The overall generator impedance is, therefore, 0.55 ohm from the two modules connected in parallel. In order to achieve the design goal for a 1-ohm tube, each Blumlein must be pulsed charged to 400 kV.

The lines are immersed in a copper-sulphate solution to avoid flashover problems at the edges of the copper sheets that compose

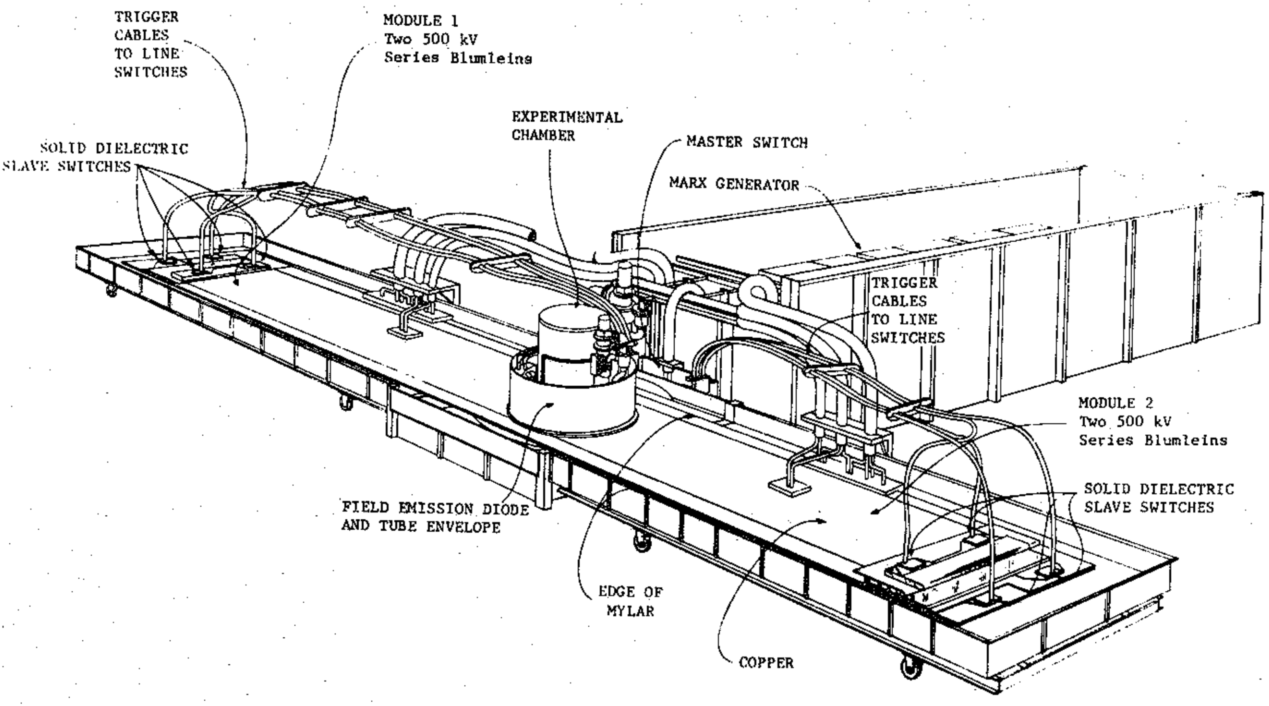


Figure 1a SNARK layout, schematic drawing.

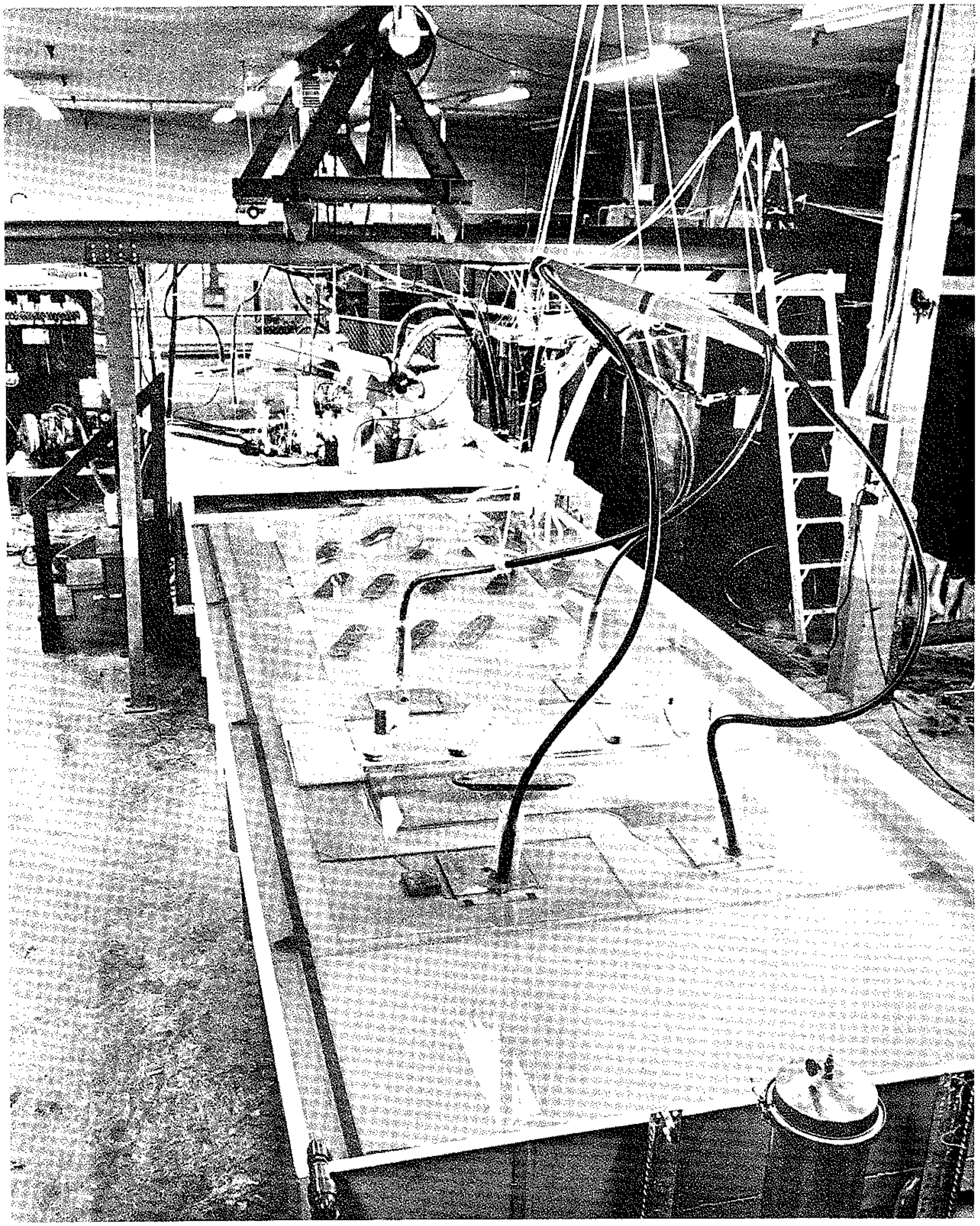


Figure 1b SNARK facility (1-MV, 50-nsec pulsed electron accelerator).

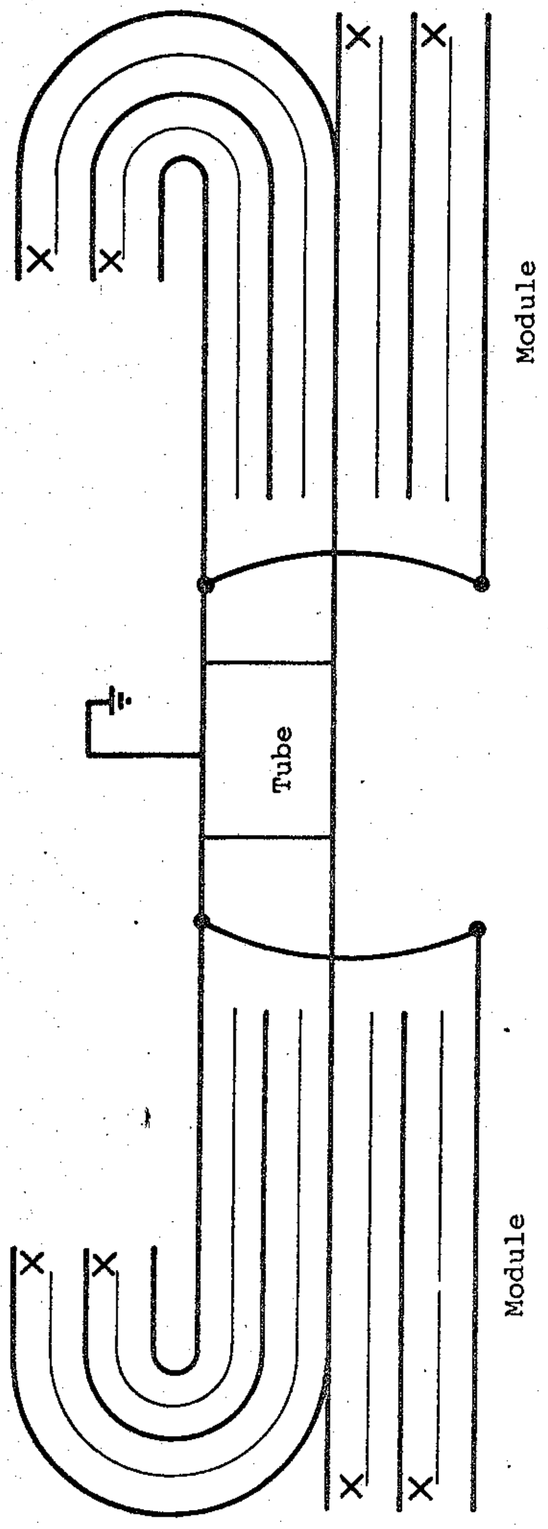


Figure 2 Schematic of SNARK.

the Blumleins. The resistive solution is allowed to form a thin tapered layer leading from the edge of the sheet by attaching a wire bead to the edge of the copper. This layer acts like a resistor in series with the edge of the line to reduce the electric fields. The lines themselves are assembled dry and vacuum impregnated, thereby easing assembly considerably and minimizing the possibility of bubble formation during operation.

The lines are pulsed charged from a separate Marx tank containing 72 0.5-μF capacitors wired in six stages. Charging cables lead from the Marx to the lines and each line is fired using a triggered slave switch. A self-firing master switch sends synchronized trigger pulses to the slave switches. These switches were originally replaceable stabbed polyethylene cards with the switch layout at the end of each module as shown in Figure 3. These switches provided current risetime in the 10^{14} A/sec range through multichanneling in each of the eight switches; however, they required an inconvenient process of switch-card changing between shots and have therefore been replaced by recently developed gas switches (Figure 4) (Reference 2). These 7.0-nH triggered rail-type switches have operated over a range of from 80 to 450 kV at currents up to 0.9 MA and have shown reproducible multichanneling for a large number of shots without requiring maintenance.

The tube configuration is shown schematically in Figure 5. A single 1.5-meter-diameter, 15-centimeter-wide cast epoxy insulator is designed to permit operation at 1 MV. The anode plate is recessed into the insulator so as to hold the gap between the anode and the cathode plate to a minimum. By cleaning and oiling the cathode plate between shots, this surface can be made to withstand over 500 kV/cm without emitting. The anode

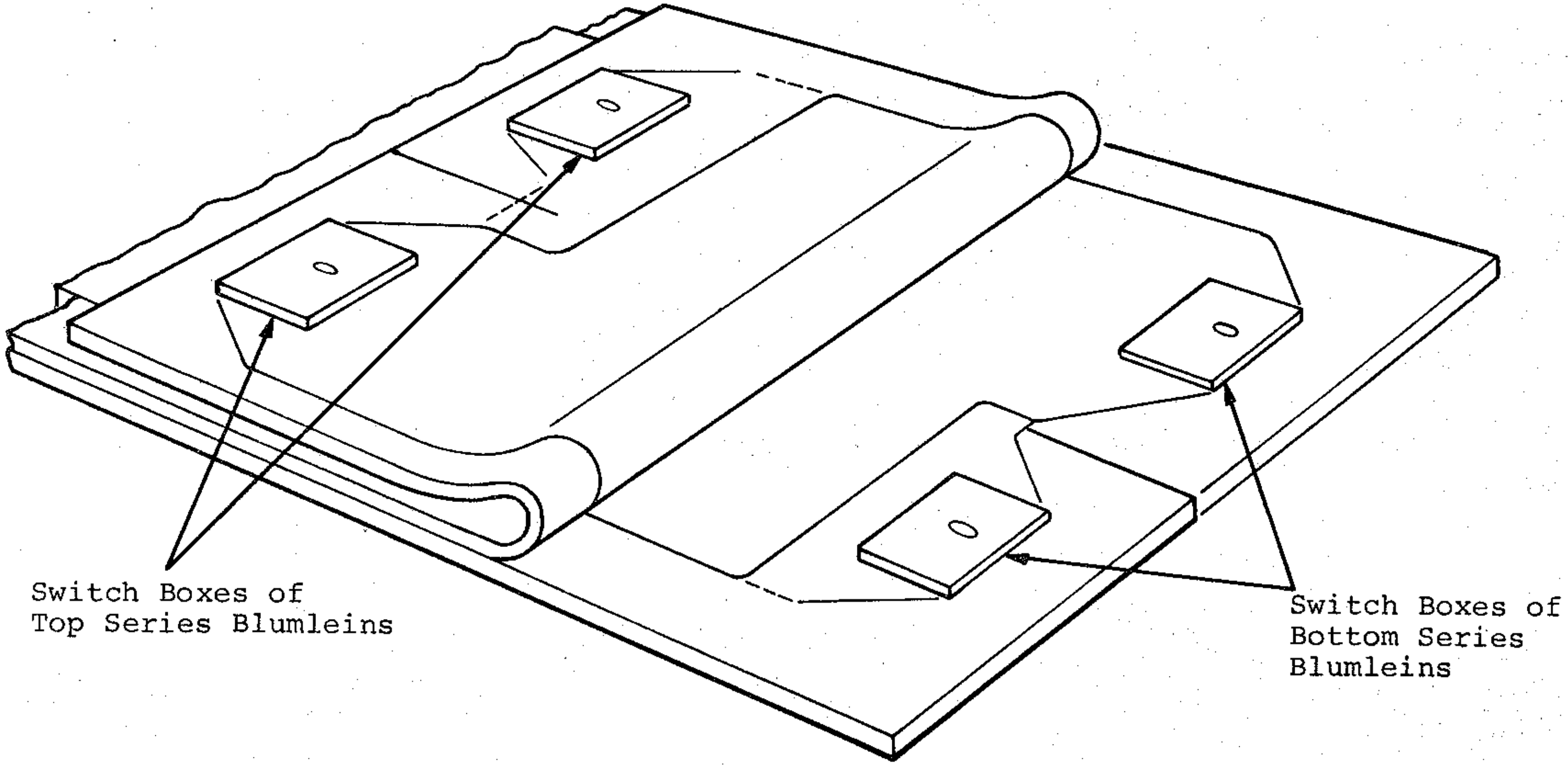


Figure 3 Switch end of module.

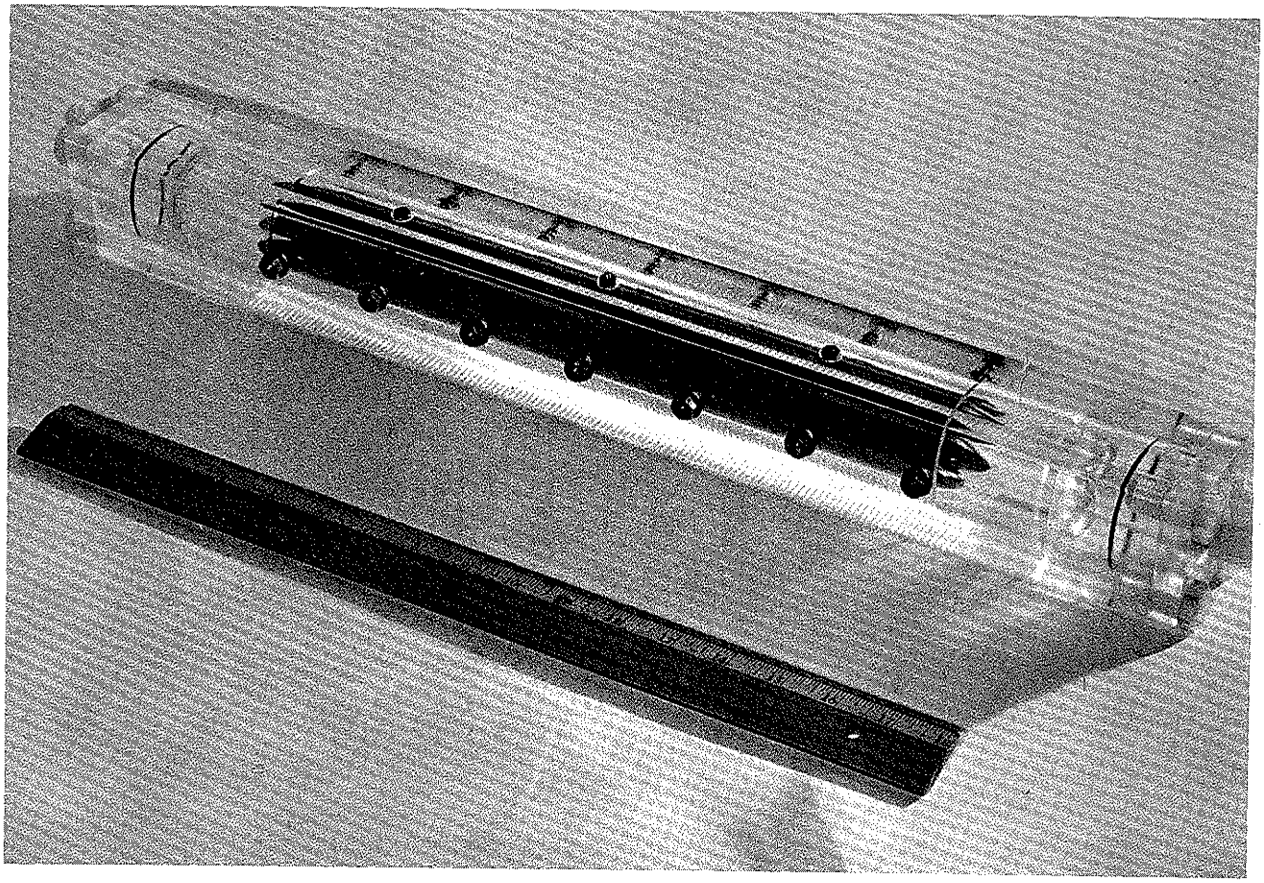


Figure 4a Assembled 8-nH, 500-kV gas switch.

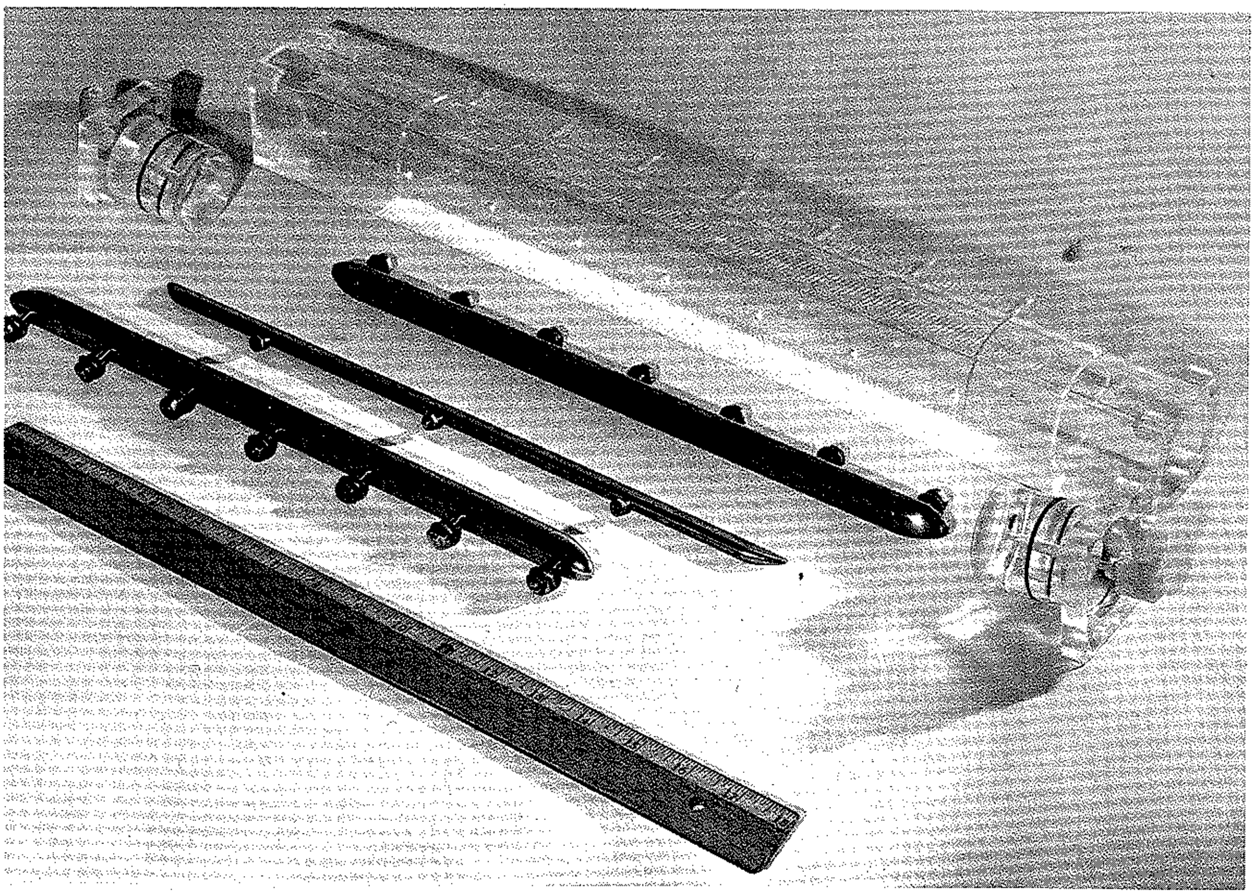


Figure 4b Disassembled gas switch showing electrodes and lucite envelope.

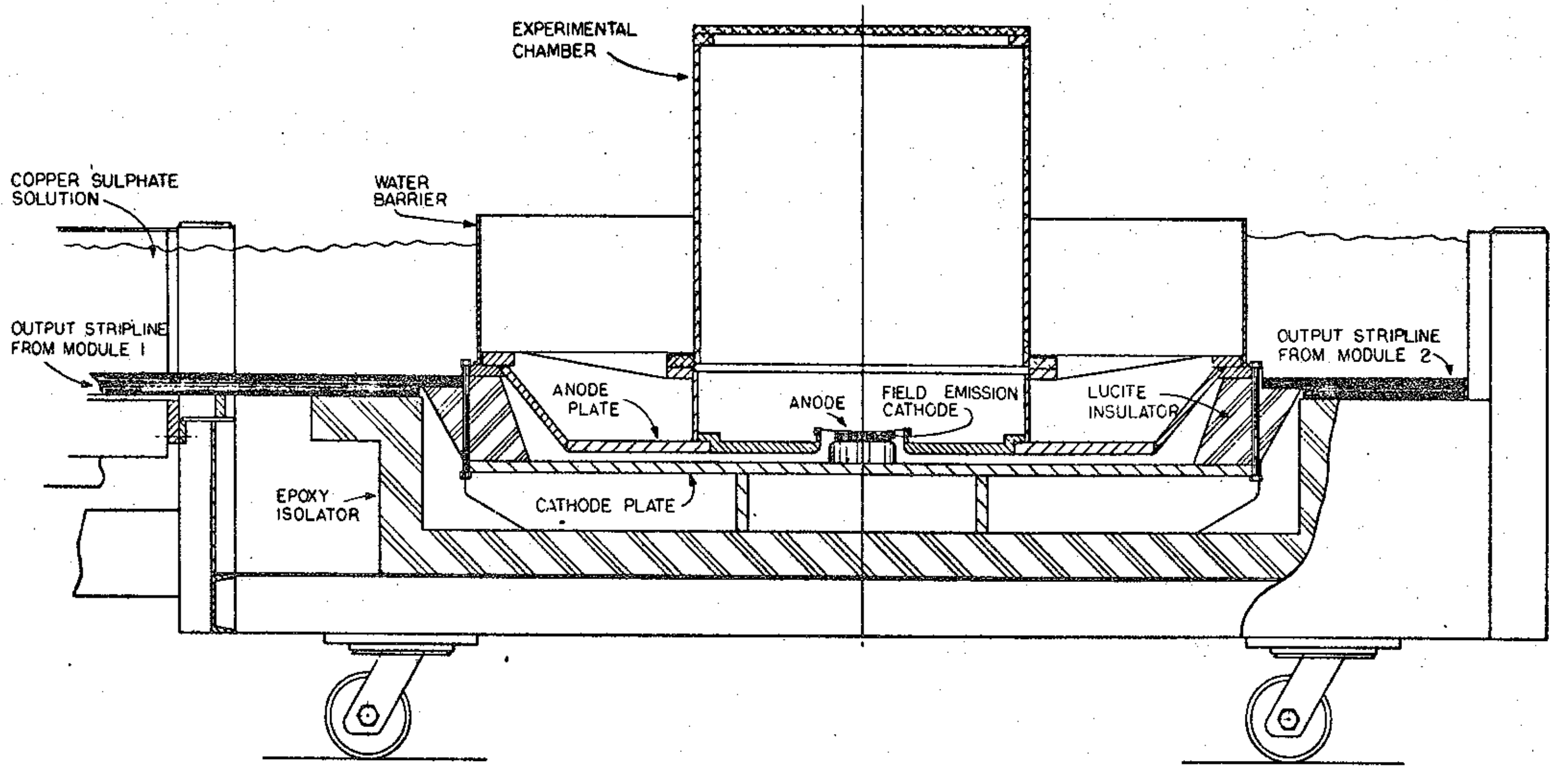


Figure 5 Tube envelope.

plate and test volume together with the associated vacuum system are removed from the tube between shots to allow access to the cathode surface and insulator (Figure 6).

The postulated output of SNARK operating at the maximum charging voltage can be deduced as outlined in Figure 7. The major energy losses occur during transfer of energy from the Marx generator into the Mylar itself, where there is a 40-percent energy loss due largely to the parallel copper-sulphate resistive line edges. There is an additional 20-percent energy loss due to series damping resistance in the Marx. Such large losses are not inevitable, but are accepted in order to minimize the possibility of line damage. A further 25-percent loss occurs due to use of a safety factor of the self-fire master switch (self-fired at 85-percent peak Marx output), but this could be reduced by using a triggered master switch fired closer to peak Marx output. Additional energy loss occurs in the transfer of energy from the charged striplines into the electron beam, the primary loss processes being impedance mismatch (between line and load) and impedance collapse. With these transfer losses and a Blumlein pulse charge of 400 kV, 65 kJ will be stored in the line and it is reasonable to expect an electron beam output in the range of 50 kJ.

The maximum measured output of the generator to date has been 56 ± 5 kJ when the lines were connected to a 0.55-ohm resistive load. Diagnostic traces from this shot and a similar 40 ± 4 kJ shot are shown in Figure 8. On the higher shot, the line was charged to slightly over 400 kV, and an edge breakdown in the Mylar near one side of the tube occurred after the main discharge pulse. Since the operating fields were well below that thought to be maximum, the reason for the failure is not known.

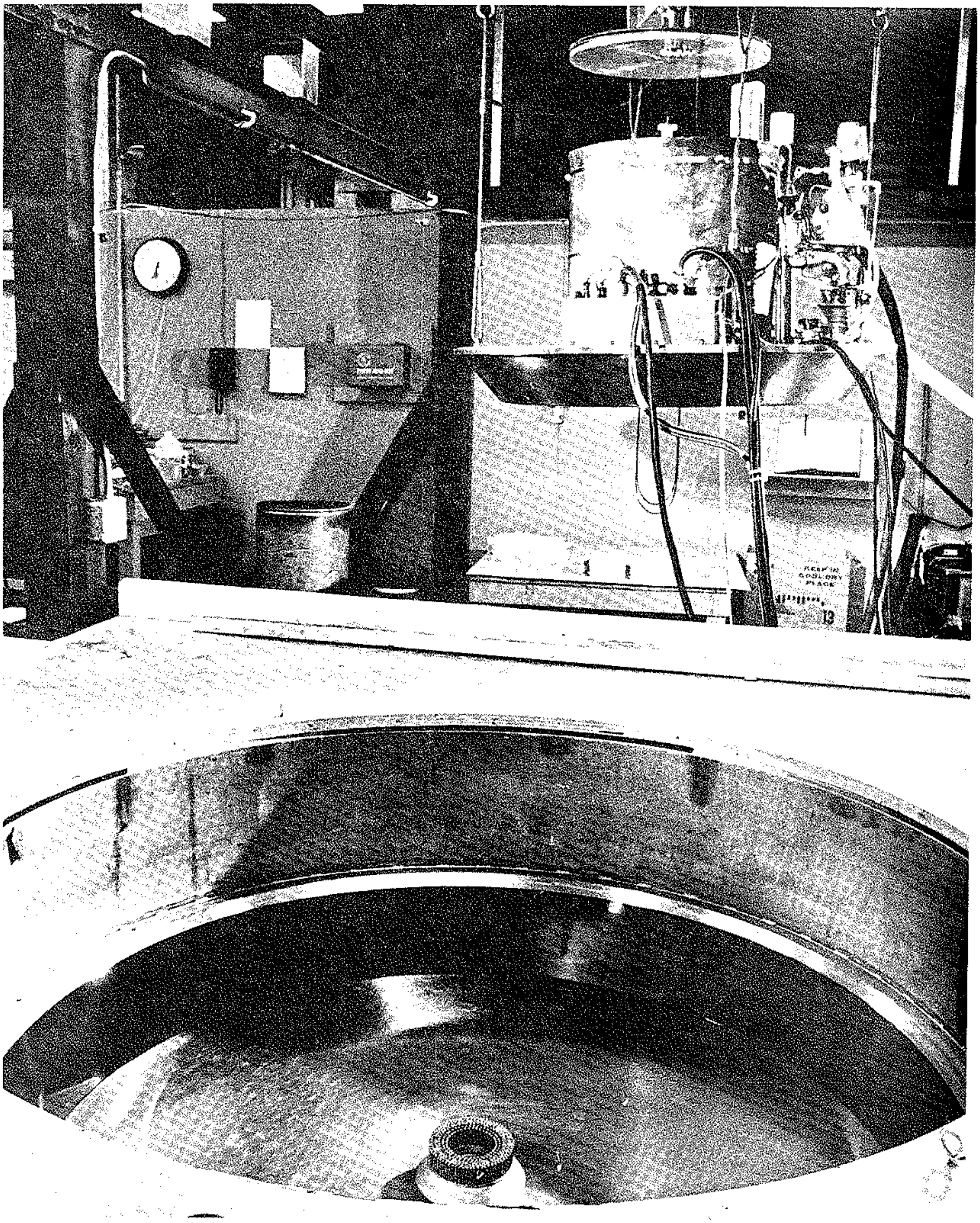


Figure 6 Tube section disassembled.

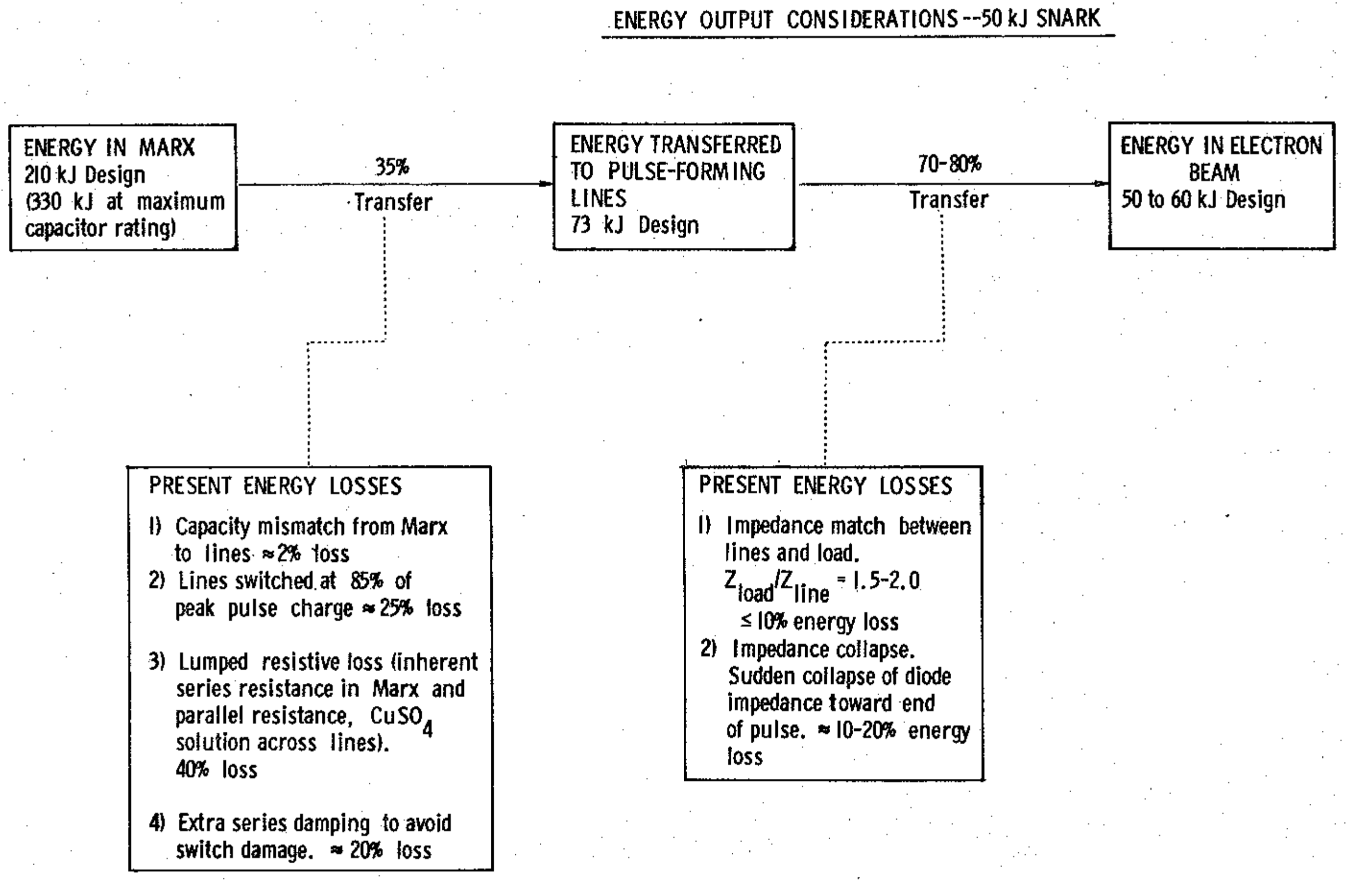
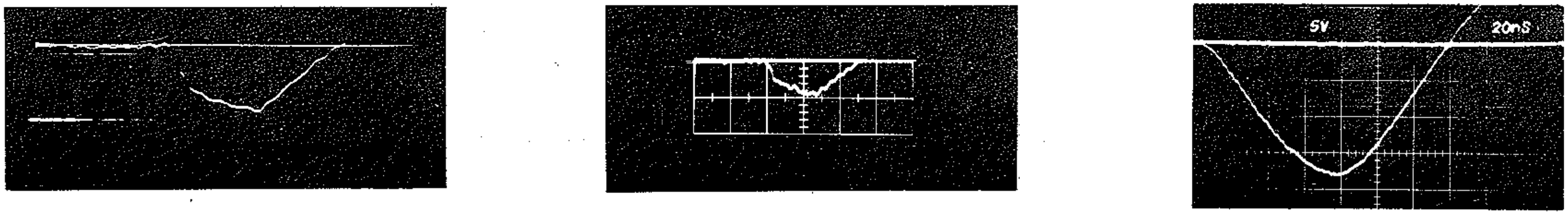


Figure 7 Energy output considerations.

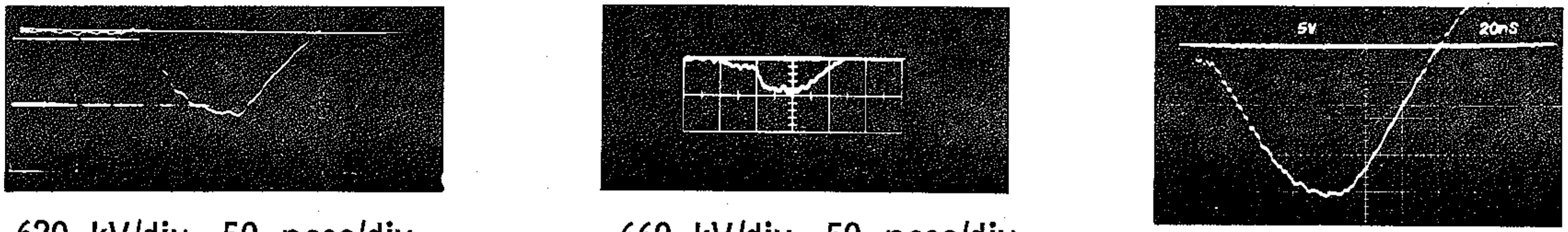


620 kV/div; 50 nsec/div
Line Voltage, Module 1

660 kV/div; 50 nsec/div
Line Voltage, Module 2

170 kV/div; 20 nsec/div
Voltage inside tube

(a) 330 kV Pulse Charge, 40±4 kJ into load



620 kV/div; 50 nsec/div
Line Voltage, Module 1

660 kV/div; 50 nsec/div
Line Voltage, Module 2

170 kV/div; 20 nsec/div
Voltage inside tube

(b) 410 kV Pulse Charge, 56±5 kJ into load

Figure 8 Output into 0.55 Ω resistive load.

Because of this type of failure, it may be necessary to add two additional series Blumleins to each module to ensure the 1-MV, 1-MA output. Further work, however, will be needed before the cause of this failure can be identified.

The pulser has reliably produced electron beam output levels of 25 kJ when the load used is a single field-emission diode. Output diagnostics from such a shot are shown in Figure 9. The diagnostics include line voltage, diode current measured with a Rogowski coil at the anode, and time-dependent photon flux using either a Compton diode or a scintillator-photodiode detector. The pulse shown here has a peak voltage of 880 kV and a peak current of 580 kA. The total energy in the beam is determined by the $\int IVdt$, after correcting V as measured by the line voltage monitor for the inductive component. As one can see from the photon pulse shape, the long current pulse after 150 nsec is occurring after the diode has shorted out, and the power pulse width is close to 60 nsec FWHM. The maximum measured output from a field emission diode has been in the 30 to 35 kJ range.

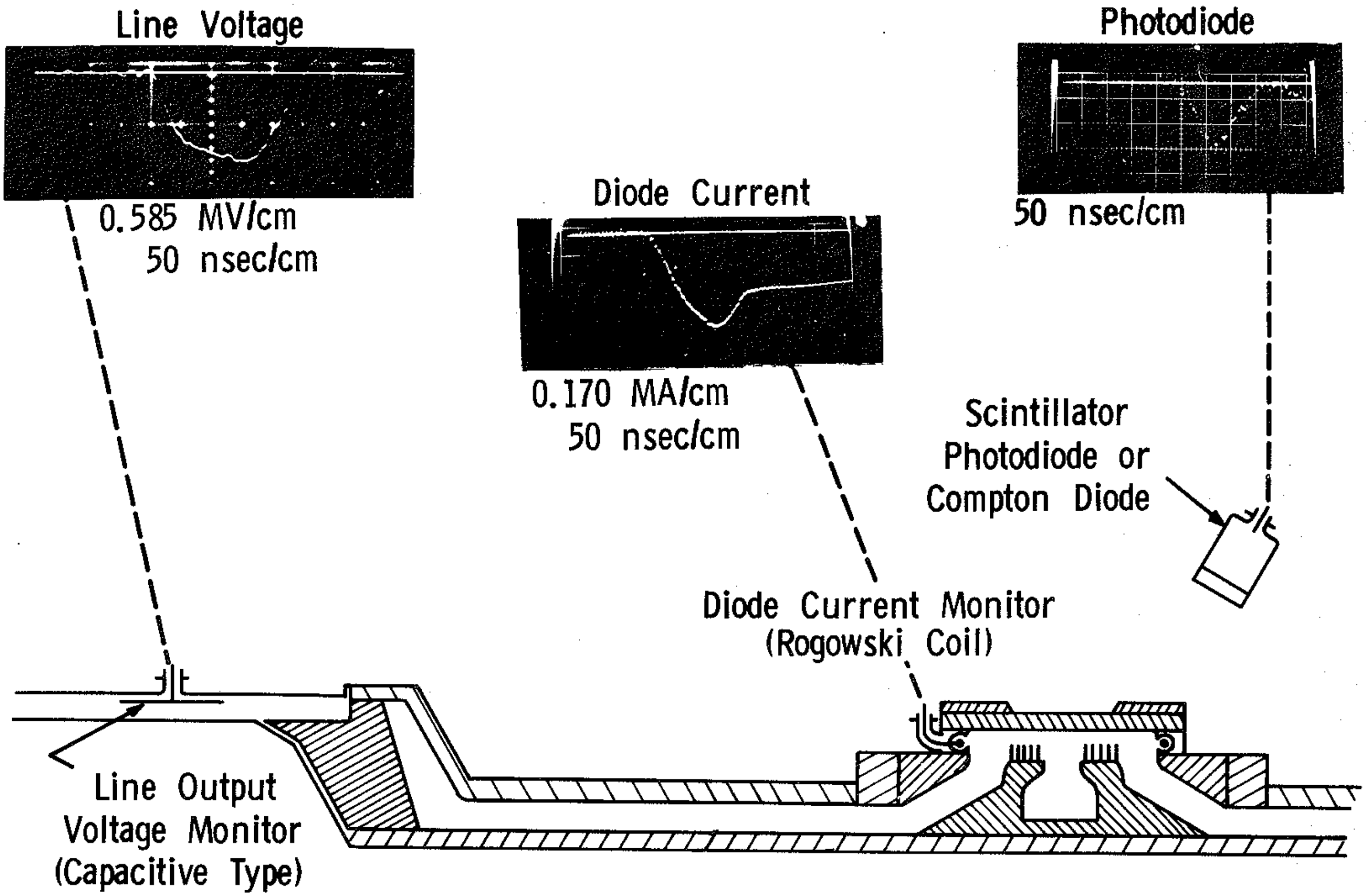


Figure 9 Output diagnostics.

SECTION 3

SCALING OF MYLAR SYSTEMS

Scaling of Mylar systems to provide multi-megamp current levels first requires consideration of current feed and inductance limitations. Linear current densities of 660 kA/meter (at 1.5-MV/cm field stress) can be achieved in a matched stripline when energy is propagated only, not stored (for example, in a matched transmission line section which connects the parallel Blumlein outputs to the load). At more conservative working fields (~ 1 MV/cm) the current feed limitation becomes 450 kA/meter. In addition, the total system inductance must be low enough that the current risetime ($t = L/R$) is substantially less than the desired pulse duration. The major load inductance contribution arises from the dielectric/vacuum interface region at the periphery of the tube. The dimensions of this insulator region are governed by the voltage holdoff characteristics of the insulator (presently 15 x 15 cm for the oiled epoxy insulator used on SNARK at 1 MV). Inductance estimates for an annular dielectric/vacuum interface are then ~ 4.5/R nH, where R is the radius (in meters) of the annular insulator. Additional inductance is added by the spacing of the anode and high voltage plates internal to the insulator envelope (~ 2 cm at 1 MV). For this reason, placement of a single small-area cathode at the center of the above large-diameter tube envelope is not a workable alternative because of the large inductance associated with current flow from the tube periphery to the central cathode. This additional inductance can be minimized by placing an annular cathode (or many separate cathodes) at the periphery of the tube.

The generator, or pulse-forming-line, inductance arises primarily from switch inductance. If the generator risetime is much less than the risetime of the tube circuit, an initial inductive voltage spike approaching twice the matched output voltage can appear across the tube insulator. A thicker insulator would then be required (to avoid flashover problems) which would increase both the amplitude and duration of the inductive voltage spike. This solution is therefore partially self-defeating. A more workable approach is to operate the system with approximately equal generator and load risetimes, which results in a peak tube voltage (including the inductive component) not exceeding the final cathode voltage by more than 14 percent (Reference 1).

The present system has, under normal operation, delivered close to 1 MA to the 1.5-meter-diameter tube fed from two sides. The circumference of the tube, 4.7 meters, is sufficiently large to feed a total of 2 MA from parallel Blumlein combinations, if two additional identical modules are added as shown in Figure 10. If multiple cathodes are placed adjacent to the insulator, the tube inductance would be an acceptable 8 nH, giving a pulse risetime (for equal generator and load risetimes) of ≈ 16 nsec.

Further scaling can be accomplished using modules which contain twice the number of Blumleins as the present ones. Each such module could deliver up to 1 MA, allowing the possibility of producing a 6-MA, 1-MV pulser, as shown in Figure 11. Tube inductance is ≈ 5 nH which would give a pulse risetime (again for equal generator load risetimes) of ≈ 30 nsec. As one can see, transport of multiple beams over distances of roughly 1 to 2 meters, followed by focusing and combination of these beams, is required. The next section describes three related approaches to handling these beams.

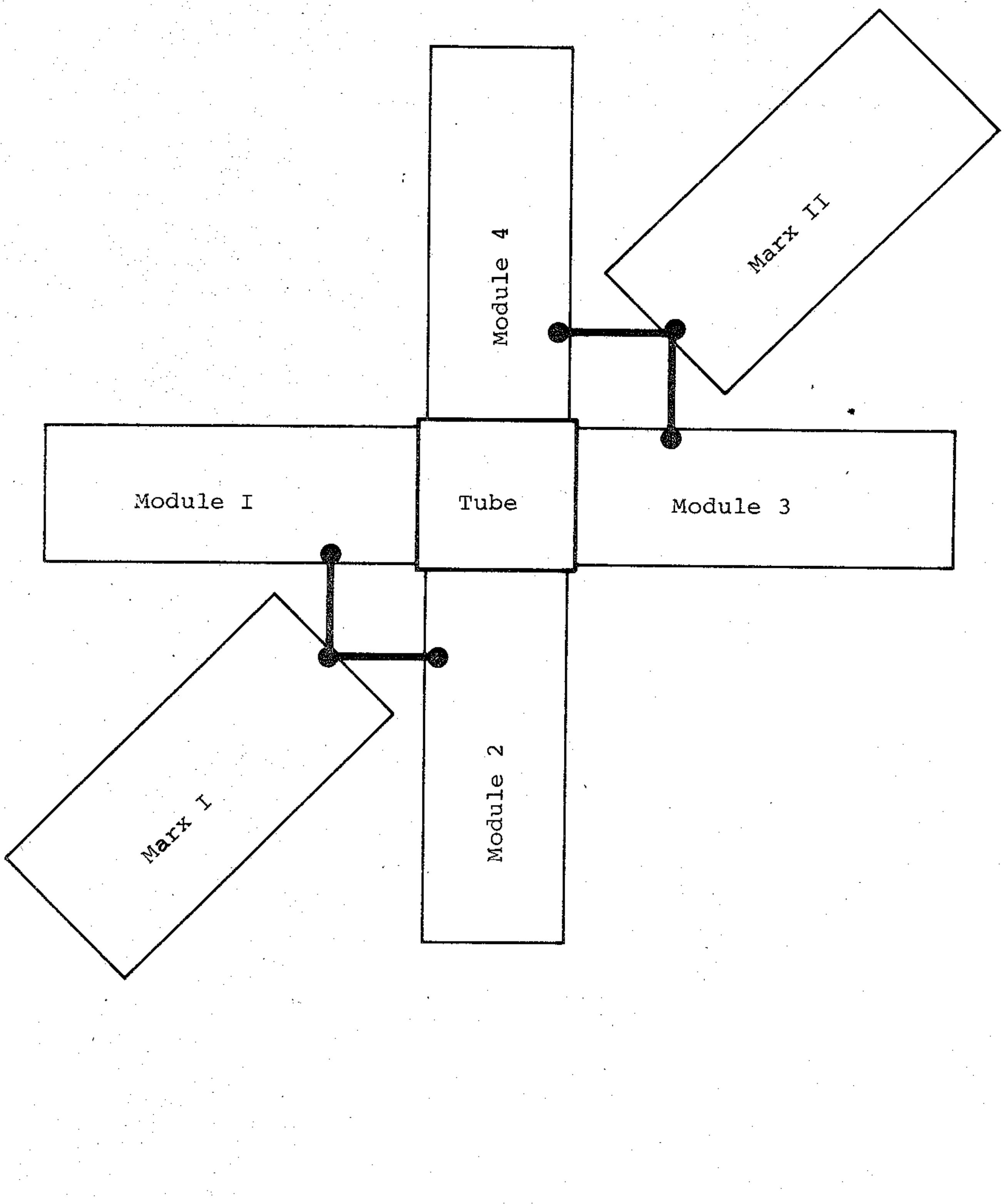


Figure 10 Four-module array.

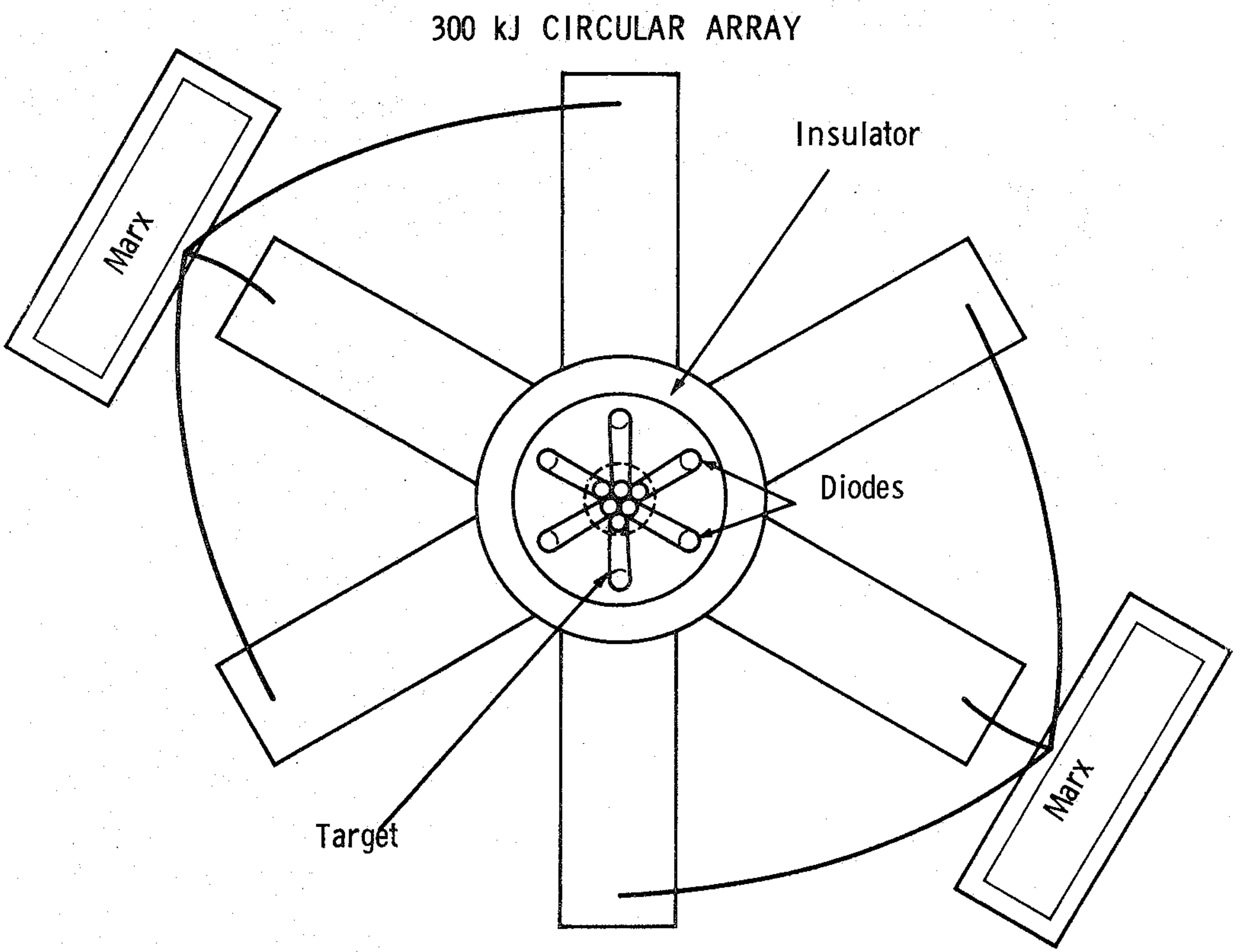


Figure 11a 1-MV, 6-MA circular array.

SECTION THROUGH SINGLE TUBE

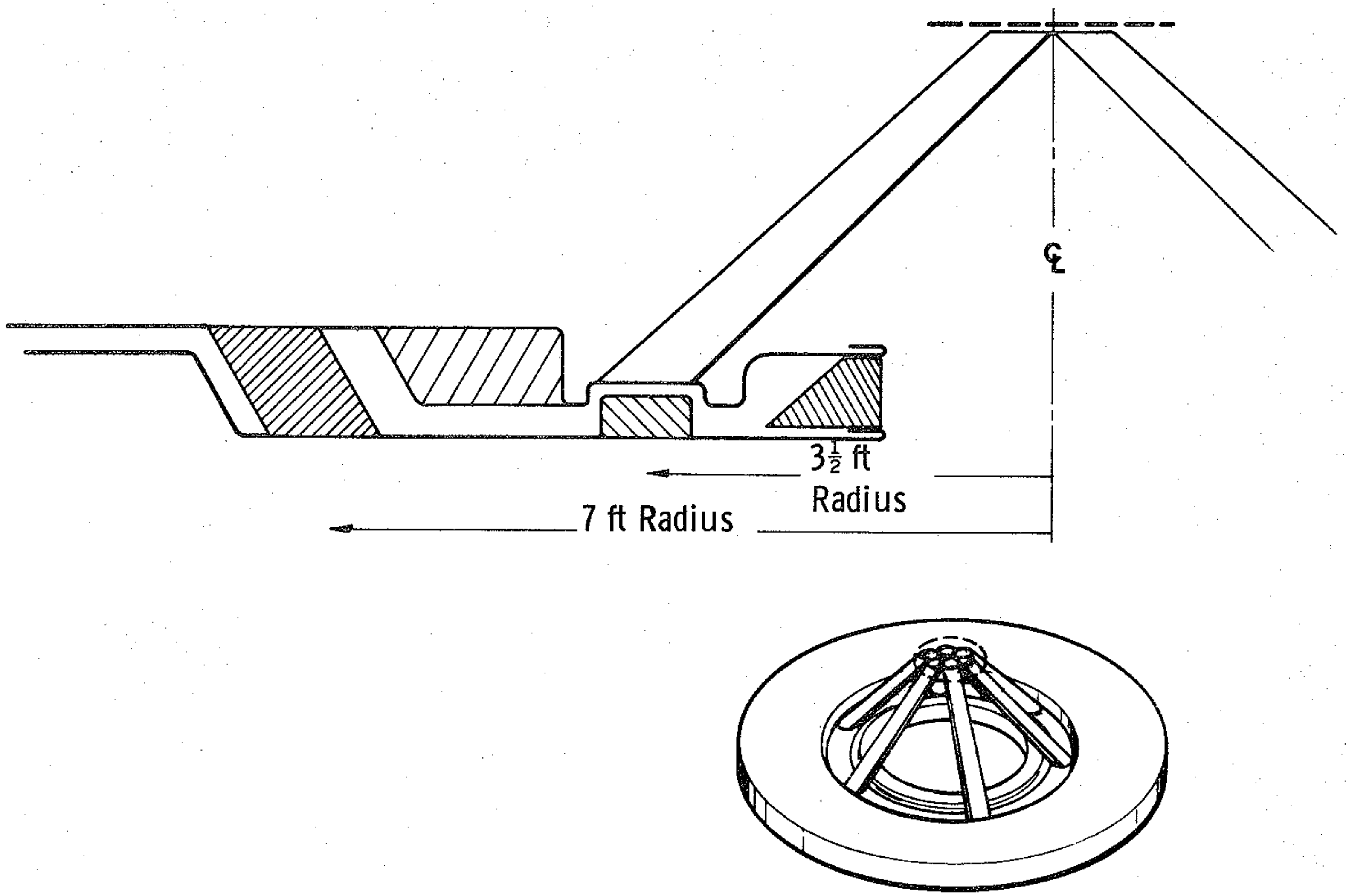


Figure 11b Cross-sectional view of tube.

SECTION 4

BEAM TRANSPORT AND COMBINATION

4.1 NEUTRAL GAS WITHOUT EXTERNAL FIELDS

The least complex system of transport and combination involves subdividing the output current into separate magnetically isolated beamlets. If the beam self-pinches in the diode, current densities of 100 kA/cm^2 are achievable. Transport in a thin-walled array of separate guide pipes could be carried out at this current density. It has been known for some time, however, that there are competing mechanisms which prevent efficient transport of pinched high ν/γ beams, when they are injected into a neutral gas without externally applied field (Reference 3). Since such beams are characterized by highly nonparaxial electron motion, a large fraction of the total beam current is lost over the first few centimeters of transport if the gas is preionized or if it is at a pressure appropriate to rapid breakdown--approximately 0.75 torr in nitrogen. After these high angle components are lost, the remaining portion of the beam propagates relatively efficiently; (an e-folding distance of approximately 250 centimeters has been observed for a 250-kV beam propagating in a 1-1/4-inch-diameter pipe). On the other hand, if gas breakdown is delayed by use of sufficiently low-pressure gas (less than 0.5 torr in nitrogen), then the net current can equal the primary current for a larger fraction of the pulse duration, resulting in better containment of the transverse energy components by the azimuthal self-magnetic field. In this case, however, the rapidly rising current creates a back EMF which decelerates the energetic electrons.

Consider, for instance, a 6-MA pulser with the current of the machine subdivided into N separate beamlets. Then, for a risetime of 20 nsec, we get E_z (V/m) = 10^{-7} dI/dt (amp/sec) = $10^{-7} \times 6 \times 10^{6}/N \times 1/20 \times 10^{-9} = 30/N$ MV/m. If the beam is propagated at pressures below 1 torr, the breakdown time will be relatively insensitive to E/P and will be equal to approximately 10^{-9} seconds divided by the pressure in torr (Reference 4). If the pressure is chosen sufficiently low to prolong the breakdown time but high enough to give collisional charge neutralization, then a reasonable value for pressure would be 0.1 torr, giving a breakdown time of 10^{-8} seconds. If we assume that the characteristic breakdown time controls the velocity of the beam front, then we can approximate the beam-front velocity by $v_f \approx V/E_z t_B$. This gives $\beta_f = 10^{-2}$ N. By comparing the beam-front velocity with the velocity of propagation of high ν/γ electrons within the beam and by requiring negligible erosion over distances of roughly 2 meters, we see that at least thirty separate beams are required. In addition, the allowable pipe diameter for efficient transport of the self-pinched beam is questionable. Previous experience (Reference 5) indicates that the low-pressure beam behavior is subject to even greater losses than that from erosion alone when the beam is contained within a relatively small-diameter conducting pipe. As a result, one is not able to closely pack the transported beams over a small output area. By creating a beam which has minimal transverse energy, many of the problems previously discussed can be eliminated. Transport of such a "cold" beam has been suggested by J. C. Martin (Reference 6).

Assuming uniform current density from a disk cathode of radius, r, anode-cathode distance, d, and no diode impedance collapse during the pulse, beam pinch (and the resulting generation of large transverse-energy components) can be avoided if the diode current is less than the critical value given in Reference 7:

$$I_{L.C.} = \frac{V^{3/2}}{136} r^2/d^2 < 8500\ \beta\gamma\ (r/d)$$

The current for each beamlet at 1 MeV must then be less than 85,000 amperes. The hypothetical 6-MA pulser would require, for example, 90 separate 65,000-ampere beams for a diode r/d of 3. In practice, impedance collapse phenomena result in average current levels higher than those predicted by the above Langmuir-Childs equation and most laboratories report better average impedance agreement with a constant of 50 to 80 instead of 136. This implies maximum values of r/d in the range 1.3 to 2, at which point the assumption of r/d >> 1 in the Langmuir-Childs impedance derivation is marginal. One possible solution is to use annular, instead of disk, cathodes to effectively decrease the emission current to values below the critical current. For example, if d = 0.5 cm, a 1.5-cm-radius annular cathode with approximately 3.5-cm^2 emitting area would produce a current density of 10 kA/cm^2 averaged over the area (7 cm^2) of a 1.5-cm-radius drift pipe. If one considers further increasing compression by using a converging longitudinal field which does not produce electron mirroring, then this provides a severe restriction on the average angle of the beam at injection into the field. Alternative approaches, such as using geometrical focusing in either very high or very low conductivity gases have been suggested, but there has been no success in stable beam combination in either neutral gas or plasmas without externally applied fields to date. Another solution to energy concentration might be to transport the low transverse temperature beams in drift pipes with a total area of ~ 600 cm^2 and to compress the beams near the target in separate, short, low-pressure, conical sections using gas focusing (References 8 and 9).

As one can see, there are several remaining unknowns related to transport and combination. Experiments are being carried out to determine minimum guide-pipe diameters for efficient transport of relatively low transverse-energy beams and to perform beam combination in low-aspect-ratio chambers. It seems, however, that more flexible and reliable advanced machines producing high energy densities can be built if one does not rely on neutral gas alone. Because of this, experiments are being conducted in the use of both longitudinal and azimuthal fields in beam transport; these are discussed in the next two subsections.

4.2 LONGITUDINAL MAGNETIC FIELDS

Experiments carried out at Cornell University and the Naval Research Laboratory (NRL) using longitudinal fields have shown that relatively weak fields are needed to obtain suppression of diode self pinch and to efficiently transport high ν/γ beams (References 10 and 11). In these experiments, the diode is extended on a stalk into the region of uniform field within a solenoid, and the target is similarly immersed at the other end of the solenoid in a region of uniform field. In both the NRL and Cornell experiments, there has been no attempt at preionization, and it is found that transport of beams with $\nu/\gamma > 10$ over

1-meter distances is typically 85-percent efficient. The results at NRL indicate that the current required to prevent self pinch in the diode is given by

$$\frac{B_{ext}}{B_{diode}} > (\nu/\gamma)(r/2d)$$

If one assumes 100-percent diamagnetism and magnetic pressure balance as suggested by Hammer (Reference 12), then the field required for efficient transport is given by $B_{ext} = k\sqrt{J}$, where

$$k = \sqrt{680\ \pi <\beta_{\perp}^2>/<\beta_{\parallel}>\ \gamma}$$

Thus a current density of 50 to 100 kA/cm^2 would require an external field of from 15 to 21 kG (if $<\beta_{\parallel}> = 0.7$). If the transport length is 2 meters, the total beam cross-sectional area is 100 square centimeters, and the total current is 6 MA, then the field energy in the transport region will be 40 kJ. With six separate beams of 16.5-cm^2 cross-sectional area each and assuming a Child's Law impedance, the diodes will have an anode-cathode gap of 2 mm. This would, more than likely, be impractical to use because of hydrodynamic response of the anode and/or cathode resulting in rapid impedance collapse. One solution to the problem of anode motion is to increase the anode-cathode distance, but to utilize plasma in the diode to reduce the effective impedance. Work carried out at both NRL and Maxwell Laboratories has indicated that a Child's Law impedance can be used in the case of large prepulse if the effective anode-cathode distance is given by a Debye length in the prepulse plasma (Reference 13). In this way impedances of 1 ohm can be achieved with a 2-inch-diameter cathode and anode-cathode distances of the order of 1 cm. With such a diode, one expects that the effect of anode/cathode motion on diode impedance will be greatly reduced. Use then of longitudinal fields with a diode operating under prepulse conditions remains one way of achieving beam extraction and transport at current densities of ~ 50 kA/cm^2.

Another way to use a longitudinal field transport system would be to propagate beams with a lower current density and to compress them at the target in a magnetic mirror. If the transported beam area is increased to 1000 square centimeters at a current density of 6 kA/cm^2, the required field drops by a factor of three and the total energy in the field remains constant. The advantage gained here is that the individual cathode radii can be increased to 6.9 cm in radius with a corresponding anode-cathode distance of 0.6 cm assuming Child's Law impedance behavior. The requirement for ten-fold compression at the target, however, is equivalent to requiring that the beam transverse energy at injection into the drift region be less than 10 percent of the total energy. Whether such a beam can be produced in a field of reasonable magnitude is still open to question.

Even with a suitably efficient means of transport using the longitudinal field, this technique has two disadvantages. The stalk required to extend the cathode into the uniform-field region of the solenoid provides an additional inductance to the diode. For instance, a reasonable inductance for such a single 1 MV/1 MA diode configuration would be 10 nH. With six such stalks at the periphery of a large-diameter single tube, the total tube inductance is increased by ~ 2 nH and the pulse risetime would be increased by about 12 nsec.

The second question relates to packing the separate solenoids close together at the target location and compressing or mixing their outputs. Even if a single mirror field is used as the final transport stage for several beams, there will be no tendency to mix the separate beams together. The longitudinal field will maintain the identity of each beam and any nonreproducibility in the diodes will be preserved at the output. Diagnosing the output uniformity during an actual shot will in itself be difficult and would greatly hamper any application.

Stallings (Reference 14) is studying a unique beam generation and transport geometry which does not require beam compression or mixing. The beam is generated from a single ring cathode at the periphery of the diode, and this annular beam is transported between two converging cones so that the total beam area is held constant (see Figure 12). In this way, there is no beam compression and current densities of tens of kA/cm^2 can be achieved over 100 cm^2 without the consequence of mirroring. The fields required to suppress the self-pinch are minimized by the hollow geometry. The obvious problem with such a scheme in future multi-megampere machines is related to the requirements for uniform emission over an edge cathode as long as 20 feet. The advantage of such a system is its obvious simplicity and the modest energy potentially needed to generate the fields. For instance, a 6-MA, 100-cm^2 hollow beam guide system would require only ~ 20 kJ field energy in the transport region even for $|\vec{B}_z| = |\vec{B}_\Theta|$ in the diode.

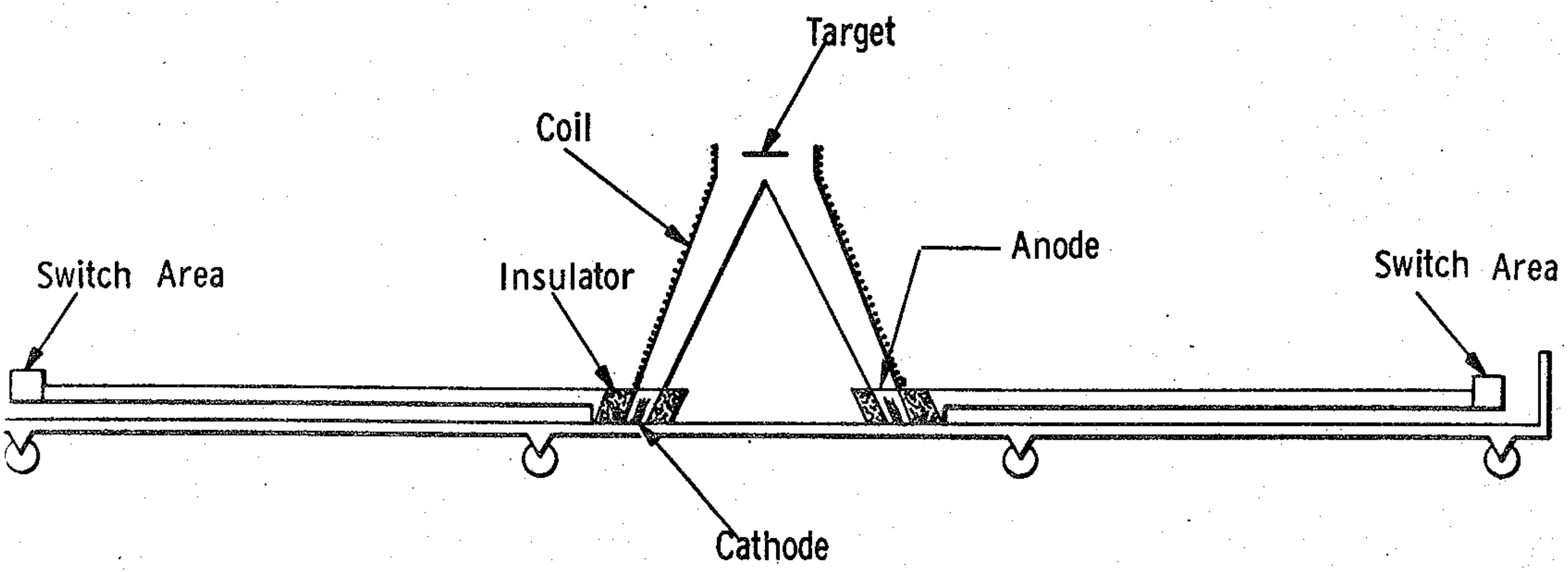


Figure 12a Conical B_Z beam generation and transport approach, schematic drawing.

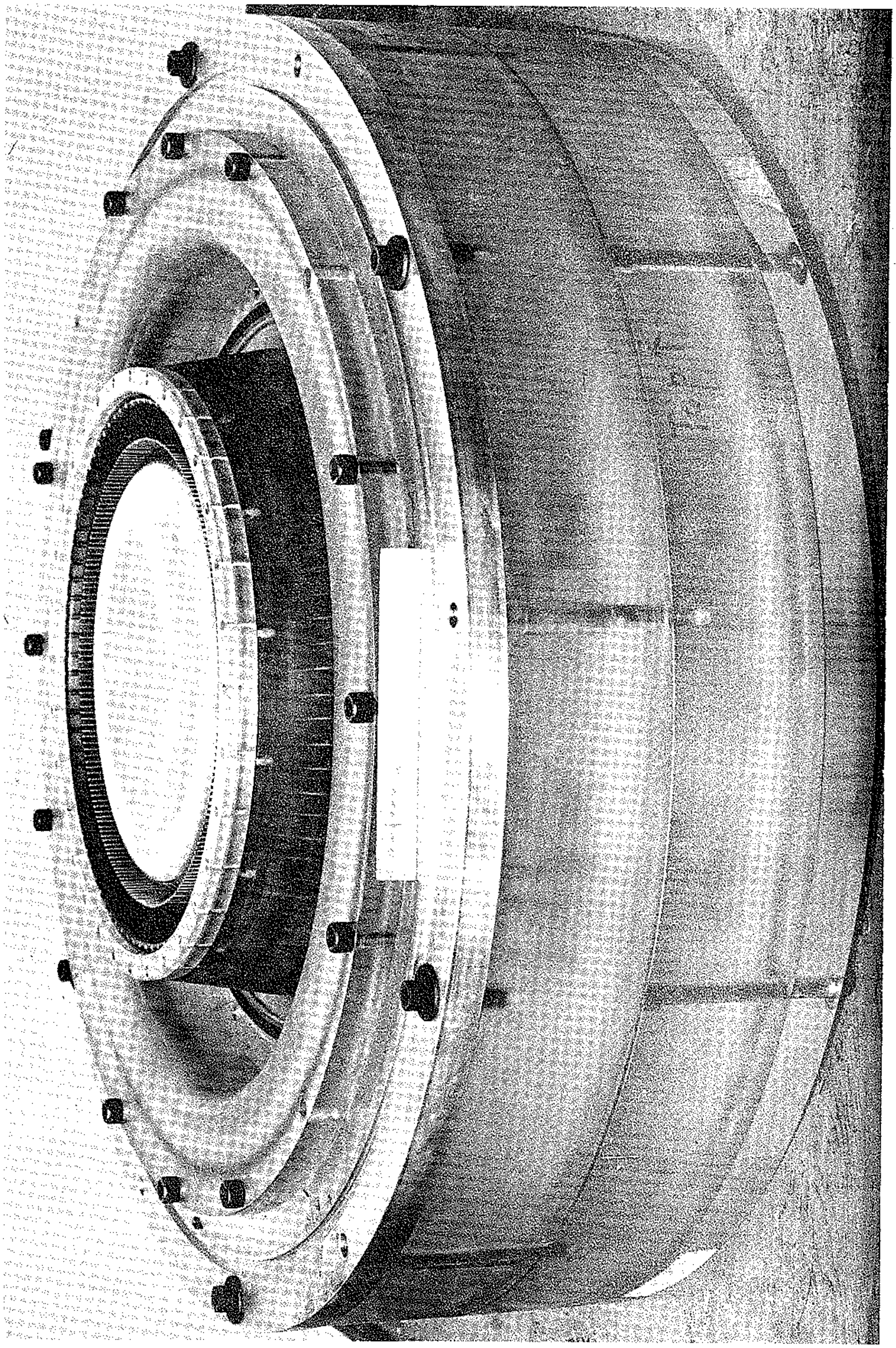


Figure 12b Annular cathode hardware for 1 MA scale test.

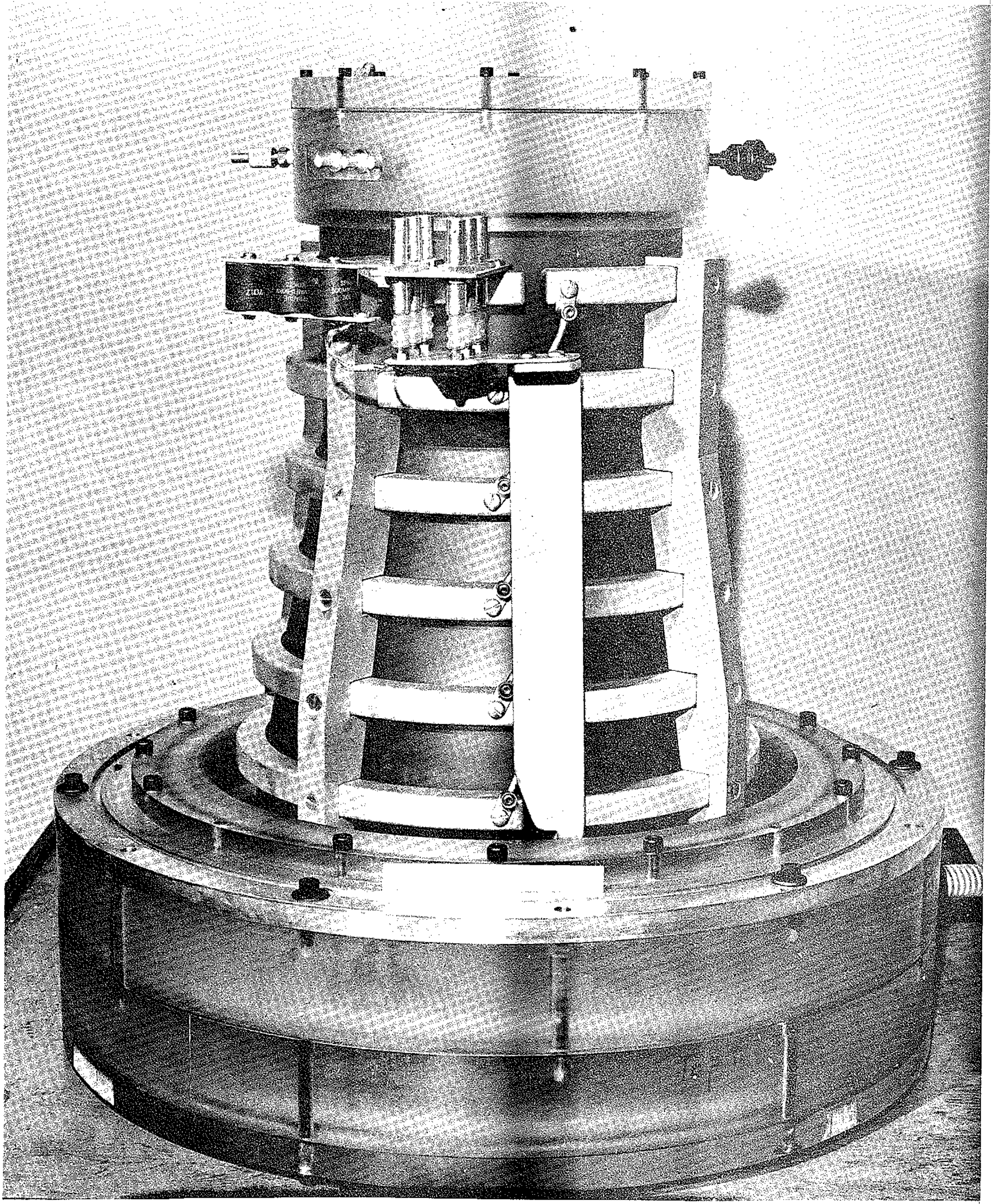


Figure 12c B_Z field coils for 1 MA scale test.

4.3 LINEAR PINCH (B_θ)

The injection of one or more high ν/γ beams into a linear pinch device for either transport or beam mixing and compression has been recently studied. Roberts and Bennett (Reference 15) first investigated the beam/pinch interaction by injecting a low ν/γ beam (3.5-MV, 30-kA) into a 50-kA pinch to determine the feasibility of using this technique to achieve higher current densities ("super-pinch"). Benford and Ecker extended the application of this technique to the transport and control of high ν/γ beams (References 16 and 17). The potential advantages of this technique over the use of a longitudinal field relate to (a) the total energy required for transport, (b) the fact that the field in the transport region does not penetrate the diode thereby allowing diode pinch and higher current densities with large cathodes, and (c) that a pinch device can in principle be used to mix several beams so as to minimize the requirements on separate diode reproducibility.

Of the three techniques, least is known about the limitations of the pinch device, as work to date has concentrated on study of beams in the 200-kA range and only preliminary beam combination or compression studies have been carried out. This technique, however, has already demonstrated efficient transport at current densities of ≈ 20 kA/cm^2 and energy flux control by containment of the beam within the collapsing pinch current sheet. The pinch has also been shown to redirect a beam injected slightly off-axis and has the potential of providing power concentration through the attraction of several peripheral beams to a central intense pinch.

SECTION 5
CONCLUSIONS

Most of the fundamental problems associated with a modular multi-megampere pulsed-electron-beam accelerator have been solved. The principle unanswered questions are those concerning transport and combination of high-intensity electron beams. The major developments in generator technology have been primarily associated with providing synchronized low-inductance switches and diodes. Beam-handling techniques have until recently been limited to beams propagating in their self-fields in initially neutral gas, but are now generally directed toward propagation in preionized gasses with externally applied fields. Of the approaches under consideration, the application of longitudinal fields to strip low-transverse-energy beams and the use of linear pinch devices to contain high-transverse-temperature beams appear to be the most promising. Experiments presently in progress should determine the feasibility of eventually constructing pulsers providing sub-MeV beams in the megajoule range.

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