

THE VEBA RELATIVISTIC ELECTRON ACCELERATOR

R. K. Parker and M. Ury

Naval Research Laboratory, Washington, D.C.

Summary

The VEBA high-current, relativistic electron accelerator has been designed and constructed at NRL for application in the study of high-power microwave sources. To meet the requirements of this study, the accelerator was designed for operation in either a short (60 nsec) or long (2.2 μ sec) pulse mode. The short-pulse mode has been in operation for nearly two years and has proven to be an extremely reliable design. The design of the long-pulse mode is now complete and component fabrication will soon be underway.

The pulse-forming network in the short-pulse mode is an unbalanced, water Blumlein with an output impedance of 9.2 Ω . The Blumlein is pulse charged by a 17 stage Marx generator which has a series capacitance of 29.4 nF. By transmission along a tapered coaxial line, the output pulse is transformed to 20 Ω and the voltage developed across a matched load increased to a maximum of 2.3 MV. The proposed conversion to the long-pulse mode will require that the Blumlein and transformer sections be removed and the diode assembly be attached directly to the oversized Marx tank. The direct coupling between the Marx and the Blumlein will then be replaced by two, nested, water capacitors which are shunted by spiral inductors. When coupled in series with the Marx, this output filter will form a three-section, voltage-fed, Guillemin (type A), pulse-forming network with a characteristic impedance of 40 Ω and a maximum output voltage of 0.9 MV.

Introduction

The past several years have witnessed a rapid expansion in efforts to exploit the unique attributes of intense relativistic electron beams. Of those areas in which this new technology has found application, perhaps the most natural is in the production of high-power microwave radiation. Indeed, the study of relativistic processes which transform electron kinetic energy into electromagnetic radiation in a wavelength range extending from centimeter to submillimeter has proven to be an interesting and productive field of research.^{1,2}

The expansion of high-power microwave research at the Naval Research Laboratory necessitated the design of an appropriate accelerator to support these studies. For this application, the accelerator must inject a magnetically confined relativistic electron beam into an evacuated drift tube which functions as the dispersive medium for the beam-wave interactions of interest. To meet the program requirements, the VEBA (Versatile Electron Beam Accelerator) was designed for operation in either a short or long pulse mode. The design objectives for the two modes are listed in Table I.

Table I

Output Voltage (MV)	Impedance (Ω)	Pulse Length (μ sec)
0.75 to 3.0	20	~0.06
0.5 to 1.0	40	~2.2

The design concept developed to meet the objectives has been summarized above. In the remaining para-

graphs, the physical and operational characteristics of the short-pulse mode are reviewed. The planned design for the long-pulse mode is also described along with the results of a preliminary microsecond diode study.

Short-Pulse Mode

The generation of the output waveform in the VEBA short-pulse mode was accomplished by coupling a conventional, pulse-charged, water Blumlein to a tapered coaxial transformer. The insertion of a matched impedance transition section between the transformer and diode vacuum envelope was required to provide an appropriate equipotential contour behind the dielectric-vacuum interface. A cross-sectional schematic of this assembly is shown in Figure 1.

Marx Generator

The VEBA Marx was designed with the intent of producing a simple, reliable, and easily maintained generator. The Marx consists of seventeen 0.5 μ F Aerovox capacitors rated at 100 kV. These capacitors are mounted approximately 5 cm above an acrylic table using small pedestals to prevent intercapacitor flash-over. The assembly is made rigid by attaching both capacitor terminals to electrodes mounted on two, rugged, UV-coupled, switch columns. To pulse charge the Blumlein, a positive charge of up to 65 kV is placed on one terminal of each capacitor. Discharge of the Marx is initiated by sending a trigger pulse to the trigaton switch which forms the initial spark gap in each column.

The capacitors are charged by a DC power supply through solid, 300 Ω , Carborundum resistors that are mounted along the switch columns. The resistors are positioned so that they not only provide a uniform potential grading along the columns but also protect the columns from excessive electrical stress. The low-resistance coupling between capacitors combined with the simultaneous triggering of both columns to give a wide range of switch operation while using only dry nitrogen as the fill gas.

When charged to 65 kV, the Marx stores 17.9 kJ. A total of 70% of this energy is transferred to the Blumlein in 0.95 μ sec, at which time the Blumlein has reached a maximum voltage of 1.5 MV. Analysis of the ringing frequency indicated that the Marx and coupling leads to the Blumlein have a total inductance of 10.8 μ H.

Blumlein

The output pulse waveform for the VEBA short-pulse mode is generated in a conventional, unbalanced, water Blumlein. For convenience, the inner diameter of the Blumlein tank was chosen to be 10.4 cm, a dimension just equal to that of the output sections of GAMBLE I and II. The 9.2 Ω output impedance of the Blumlein was achieved by setting the impedance of the outer coaxial line at 3.4 Ω and that of the inner at 5.8 Ω . This degree of mismatch was required to raise the breakdown voltage for streamers initiated along the surface of the center conductor to 2.0 MV. To reduce the probability of breakdown from the output edge of the intermediate conductor, a 2.54 cm diameter

stress reduction ring was added to this edge. This Blumlein configuration generates a 60 nsec pulse (FWHM) and presents an 11.2 nF capacitance to the Marx during the charge sequence.

The Blumlein discharge sequence is initiated by closure of the over-volted water switch which terminates the inner line. This switch is formed by the hemispherical termination of the center conductor and a 1.91 cm diameter brass rod which projects axially from the inner surface of the intermediate conductor. The switch geometry was carefully designed to provide an equal probability of streamer initiation from either electrode. With the small diameter rod fully withdrawn, the switch will trigger at 1.7 MV to eliminate the possibility of inadvertent over-charging of the pulse-forming network.

To minimize the acquisition costs, the tanks in the Blumlein, transformer, and transition sections were fabricated from 1.25 cm thick aluminum sheets. The center conductor of the Blumlein and transformer were similarly fabricated from 0.64 cm thick aluminum sheets. The intermediate conductor in the Blumlein, however, was constructed using 0.32 cm thick stainless steel to avoid any possible damage or deformation which might result from the shock waves generated by the transfer of a maximum of 12.6 kJ through the water switch. To minimize electrode erosion, the active contours within the water switch were protected by Elkonite caps. Experience has shown that the extensive use of aluminum in the VEBA pulse line has not presented a problem.

Transformer

Once beyond the intermediate conductor of the Blumlein, the center conductor begins a long 2.18 m taper from an initial impedance of 9.2 Ω to a final impedance of 20.3 Ω . The voltage step-up ratio within the transformer is therefore 1.49. At a distance of 70 cm from the Blumlein, the center conductor of the transformer is connected to ground by a 1.5 μ H inductor which limits the prepulse to less than 150 kV. Near the transformer output, water breakdown is predicted to occur at a voltage of 3.1 MV. Since the system has been successfully operated at a maximum output

voltage of 2.8 MV with no evidence of water breakdown, the usual expression for breakdown would appear to be valid in spite of the high degree of field nonuniformity in this region.

Transition Section and Output Tube

The decision to use a high-impedance, water-dielectric transformer in conjunction with the Blumlein added a unique complication to the design of the output tube. With water as the dielectric medium, a 20 Ω coaxial line has a large ratio of outer to inner electrode radii. Such a configuration produces an equipotential distribution which is poorly suited for transition through the acrylic-vacuum interface of the output tube. This complication was overcome by including an oil-filled transition region between the transformer and the output tube. The function of this region is to lift the equipotential contours to larger radii and still maintain an approximately 20 Ω impedance. This transition could not be accomplished in water because the resultant capacitance would seriously degrade the risetime of the output waveform.

The final selection of the center conductor dimensions was based on the availability of standard dished heads. The 61.0 cm diameter head which was used gave the cylindrical section of the transition region a 21.6 Ω impedance. A capacitive voltage divider to monitor the output voltage was then located midway through the transition region to take advantage of the cylindrical geometry.

The center conductor within the transition region is terminated at the output tube by a field shaping contour which penetrates the planar acrylic insulator. This contour was carefully tailored using a series of computer calculations to optimize the electric field distribution along the critical acrylic-vacuum surface of the insulator. A plot of the calculated field distribution along this interface, based on the final electrode contours is shown in Figure 2. The upper limit to the output voltage is defined by the sharp rise in the field distribution near the anode triple point. The peak field near the triple point corresponds to 75 kV/cm with 1 MV on the tube. From Milton's data⁴, the critical field for surface flash-

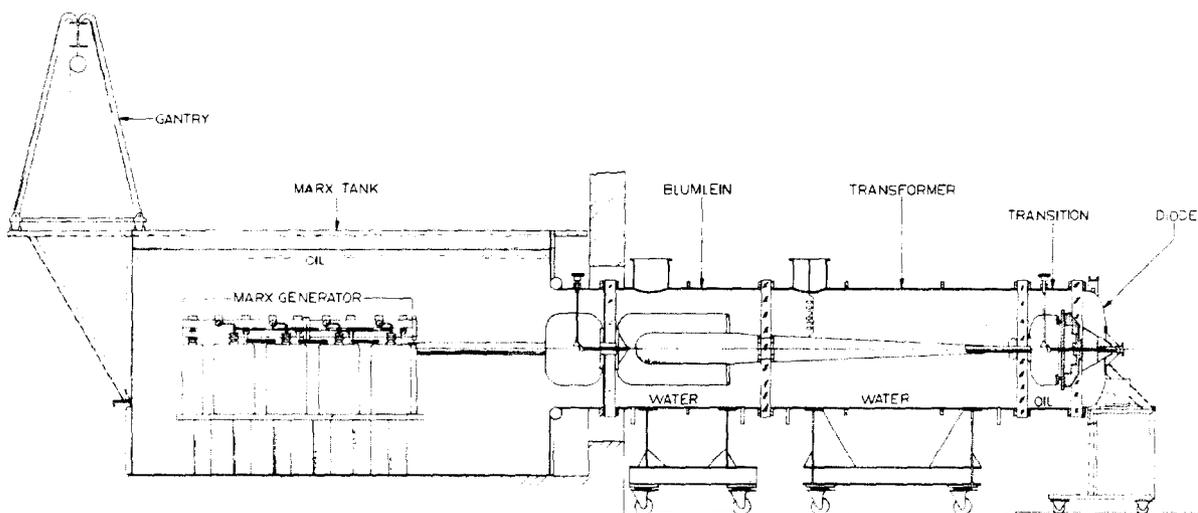


Figure 1. A cross-sectional schematic of the VEBA short-pulse mode.

over on Lucite at large angles and with short duration pulses should be in excess of 315 kV/cm. The VEBA tube should, therefore, withstand short duration output voltages on the order of 4 MV. The breakdown limit of this design has never been tested since the maximum output voltage attained to date has been 2.8 MV. With a pulse duration of several microseconds, the critical breakdown field is reduced to 197 kV/cm. In the long pulse mode, the insulator should, therefore, withstand voltages somewhat less than 2.6 MV.

Although the breakdown voltage predicted from the data shown in Figure 2 was more than adequate for the contemplated operation of the accelerator, the field distribution is not ideal. An ideal design would minimize the field distribution at both triple points. In this case, a minimum at the anode triple point was not possible because the anode contour on the vacuum side of the triple point is defined by a standard, stainless-steel dished head. Unfortunately, the inner diameter of the best available head was slightly smaller than the corresponding diameter of the tank used in the transition region. To reduce the effects of this mismatch a 9.5 mm spacer ring separated the radiused edge of the dished head from the acrylic surface. The field distribution shown in Figure 2 was achieved by tapering the inner edge of the spacer ring at 45° to the surface.

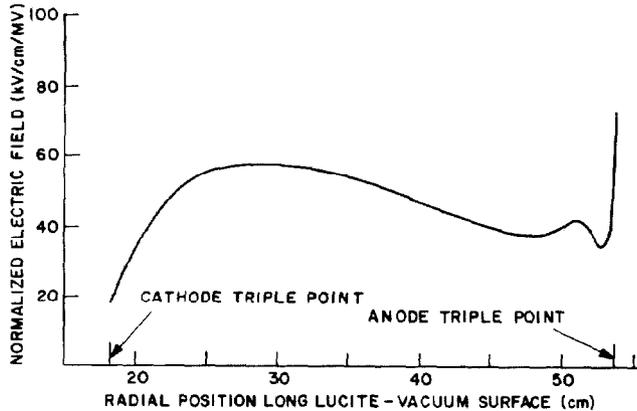


Figure 2. Distribution of electric field along the Lucite-vacuum surface.

Operational Characteristic

For the production of microwaves, the output tube is terminated in a magnetized injection diode which accelerates a cylindrically symmetric relativistic electron beam into the drift region. Since this diode configuration does not require an anode foil, there is no vacuum loss following each pulsed discharge. Once the output tube, drift region, and microwave antenna are evacuated, system operation can be continued for perhaps 100 to 200 shots before the accumulation of debris on the tube insulator leads to surface flashover. Given this advantage of a high firing rate, the total number of accumulated shot on the system is now approaching 4,000. With the exception of several initial difficulties which were quickly identified and corrected, the VEBA has proven to be quite reliable in its short-pulse mode. Major Marx maintenance has been limited to removal of the switch columns after approximately 2500 firings for cleaning.

A typical set of output voltage and current waveforms produced by discharging the system into an injection diode are shown in Figure 3. For this shot

a 4 cm diameter stainless-steel cathode was positioned in the fringing fields of the solenoid at a distance of 3.8 cm from the entrance of the 4.76 cm diameter drift tube. With a charging voltage of 48 kV on the Marx, the pulsed voltage developed across the diode had a peak amplitude of 2.05 MV and a duration of 60 nsec. The total current in the diode reached a maximum of 41 kA. Of the total electron flow, only 13 kA reached the far end of the drift region. A large fraction of this difference can be attributed to shunt losses in the diode. With a fixed setting of the water switch, the shot-to-shot reproducibility of the output voltage has been approximately $\pm 8\%$.

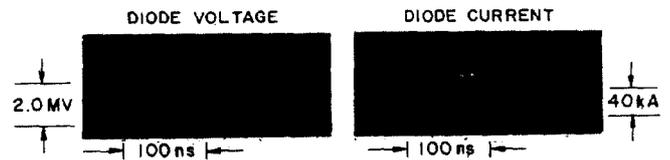


Figure 3. Typical voltage and current waveforms generated in the short-pulse mode

Long-Pulse Mode

Proposed Design

As described in the introduction, the VEBA design was required to incorporate a capability for easy conversion to a long-pulse mode of operation. The critical features of the proposed conversion are shown in Figure 4. Comparison with the cross-sectional schematic of the short-pulse mode (Figure 1) shows that the pulse-forming network has been removed and the diode assembly connected directly to the Marx tank. The direct coupling between the Marx and the Blumlein has also been replaced by an appropriate output filter. This filter combines with the Marx to form a three-section, voltage-fed, Guillemin (type A), pulse-forming network which will deliver an output pulse that approximates a flat-top waveform with parabolic rise and fall.

A simplified schematic of the three-section Guillemin circuit is shown in Figure 5. In the schematic, components C_m , L_m and R_m represent the series capacitance, inductance, and resistance of the fully erected Marx. The output filter is formed by the two parallel resonant sections $L_1 - C_1$ and $L_2 - C_2$. Appropriate values for these components were then derived from the Guillemin theory⁵ which specifies these values in terms of the characteristic impedance Z_0 (ohms) of the network and the base-to-base duration t_0 (seconds) of the output pulse. The Guillemin relationships for the three-section network are as follows:

$$C_m = 0.432 t_0 / Z_0 = 26.0 \text{ nF}$$

$$L_m = 0.170 Z_0 t_0 \geq 12.8 \text{ } \mu\text{H}$$

$$C_1 = 0.392 t_0 / Z_0$$

$$L_1 = 0.0118 Z_0 t_0$$

$$C_2 = 0.232 t_0 / Z_0$$

$$L_2 = 0.0768 Z_0 t_0$$

In using these equations to design an output filter, the capacitance of the Marx defines the slope

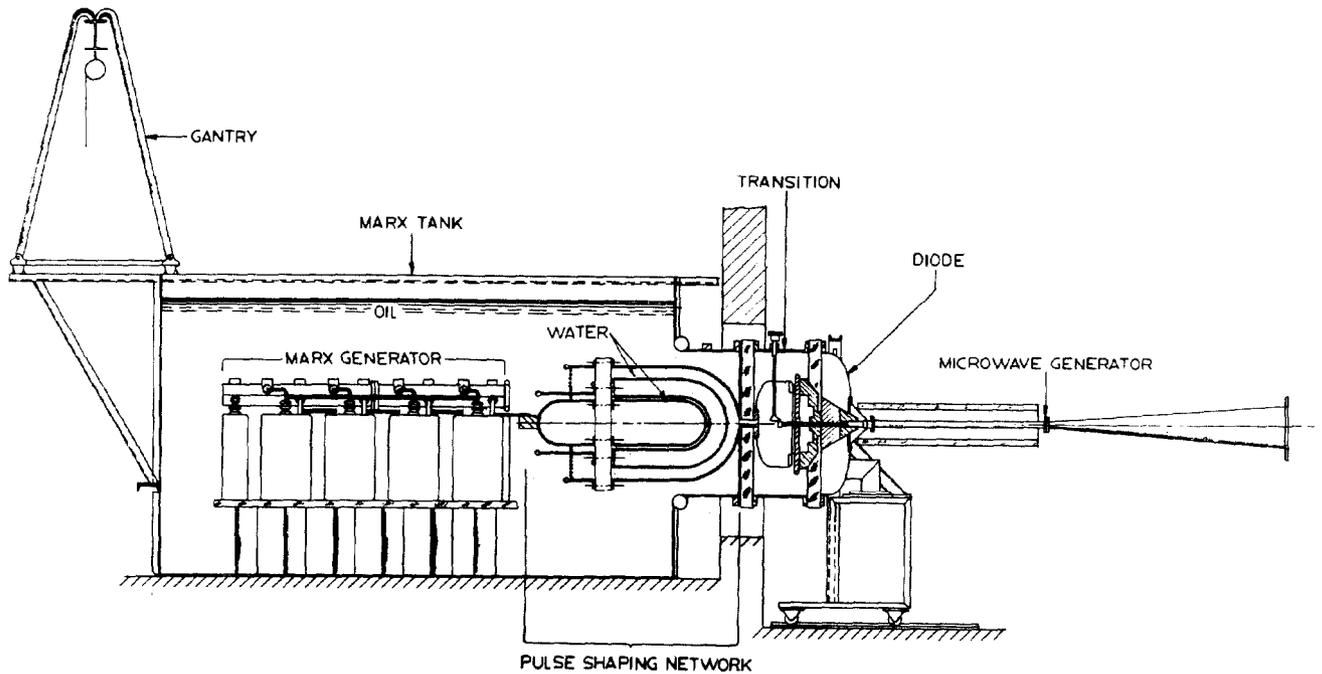


Figure 4. A cross-sectional schematic of the VEBA long-pulse mode.

of a linear relationship between the network impedance and the output pulse duration. The Marx inductance then limits the minimum admissible pulse duration. The values of the Marx parameters listed above are predicated on the present Marx being upgraded to a total of 19 stages. This modification will be necessary to obtain the desired 1 MV output. Provisions for this modification were incorporated in the initial Marx layout. With the modified Marx, the minimum pulse duration will be 2.19 μ sec. Since the effective resistance of the injection diode was in the range of 25 to 50 Ω , the characteristic impedance for the planned VEBA network was set at 40 Ω . This selection yields a pulse duration of 2.41 μ sec and will require the addition of a 3.6 μ H inductor in series with the Marx.

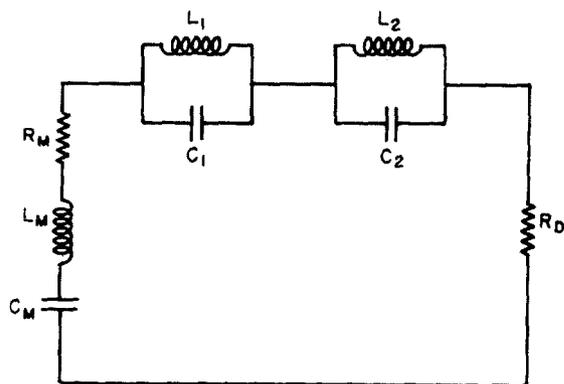


Figure 5. Simplified schematic of a three-section, voltage-fed, Guillemin (type A), pulse-forming network.

Output Filter

The proposed configuration for the output filter takes the form of two, nested, water capacitors shunted by single-layer, radial inductors. The cylindrical-hemispherical, capacitor geometry shown

in Figure 4 was chosen not only to achieve a compact design but also to simplify the dimensional analysis. Specification of the capacitor dimensions was determined by the combined requirements to match the capacitances derived from the Guillemin theory and to avoid water breakdown. As the network is discharged, the voltage waveform developed across the water capacitors is sinusoidal. The probability of water breakdown is, therefore, highest when the inner conductor within the hemispherical region is charged positively with respect to the outer conductor. When coupled with the additional requirement that the probability of breakdown be equal within both capacitors, these conditions lead to the following set of equations which determine the acceptable dimensions in the water capacitor conductors,

$$C_1 \text{ (nF)} = 0.0445 \left[\frac{\ell}{\ln(r_2/r_1)} + \frac{r_2 r_1}{r_2 - r_1} \right]$$

$$C_2 \text{ (nF)} = 0.0445 \left[\frac{\ell}{\ln(r_4/r_3)} + \frac{r_4 r_3}{r_4 - r_3} \right]$$

$$n_1 = \frac{F_B(r_1)}{F(r_1)} = \frac{0.3 (r_2 - r_1) r_1}{v_1 t_1^{1/3} (2\pi r_1^2)^{0.1} r_2}$$

$$n_2 = \frac{F_B(r_3)}{F(r_3)} = \frac{0.3 (r_4 - r_3) r_3}{v_2 t_2^{1/3} (2\pi r_3^2)^{0.1} r_4}$$

$$n_2 = n_1 \text{ and } n_2 > 1$$

In the above equations, all physical dimensions are measured in centimeter, the voltage in megavolts, and time in microseconds. The included parameters were defined as follows:

ℓ - cylindrical length of the output filter
 r_1 and r_2 - inner and outer radii of capacitor C_1

- r_3 and r_4 - inner and outer radii of capacitor C_2
- $F_B(r)$ - threshold field for water breakdown in the hemispherical region of the water capacitors
- $F(r)$ - maximum electric field within the water capacitors
- V - maximum voltage developed across the filter capacitors
- t - effective time for water breakdown within the water capacitors
- n - water safety factor within the capacitors

For dielectric breakdown, the effective time has been defined as that interval during which the electric field exceeds 63% of its maximum value.

The voltage waveforms developed across critical elements were calculated using the NRL transmission line code (TEMP)⁶. To use this code, the lumped-parameter network components were replaced by equivalent transmission line segments. The results of this calculation are shown in Figure 6 for the case of a 100 kV charge on the modified Marx and a 44 Ω load resistance.

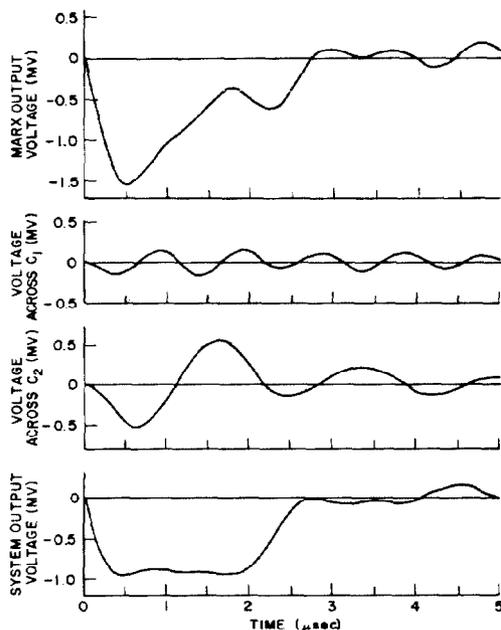


Figure 6. Voltage waveforms developed across critical elements of the three-section, Guillemin network.

The geometrical equations provide a unique solution for the capacitor radii once the cylindrical length and the water safety factor have been specified. The acceptable range for these independent parameters is constrained by the following considerations. From Figure 4, it can be seen that a continued expansion in the radial dimensions of the output filter is limited by an increasing probability for oil breakdown between the filter and the Marx tank. A balanced solution would, therefore, require that the water safety factor be set equal to that in the oil. The physical length of the filter network is limited by the intended function of the capacitors. If the water capacitor is to respond as a lumped parameter

circuit element and not a transmission line, the energy transit time along the capacitor must be short compared to the period of oscillation within capacitor C_1 .

The effects of these constraints are plotted in Figure 7 which shows the calculated solution of r_4 as a function of l for two values of the water safety factor; $n = 1.0$ and $n = 2.0$. The solutions for which $n = m$ (m is defined as the oil safety factor) are denoted by the balanced design line. The vertical line at $l = 90$ cm corresponds to $T_1/\tau \approx 20$. Note that the region of interest ($m > 1$, $n > 1$, and $\tau \ll T_1$) falls well within the physical limits of the Marx tank. To provide a useful figure merit, those solutions which store an energy density \mathcal{E} greater than 0.01 J/cm^3 in capacitor C_2 fall to the left of the annotated line. This value represents an approximate practical upper limit to the energy density that can be achieved in pulsed systems using conventional dielectrics. To substantially exceed this limit, the systems designer is currently limited to a choice of either water or Mylar. As seen from the figure, the design parameters selected for the proposed system are rather conservative and correspond to a balanced safety factor of 1.7. This is equivalent to operating within 60% of breakdown.

The output waveform shown in Figure 6 would result if the modified Marx were charged to 100 kV and then discharged into a 44 Ω resistive load. Under these conditions, the output pulse has a maximum amplitude of a 920 kV and a duration (FWHM) of 2.15 μsec . The energy delivered to the load during the FWHM of the power pulse is 39.8 kJ.

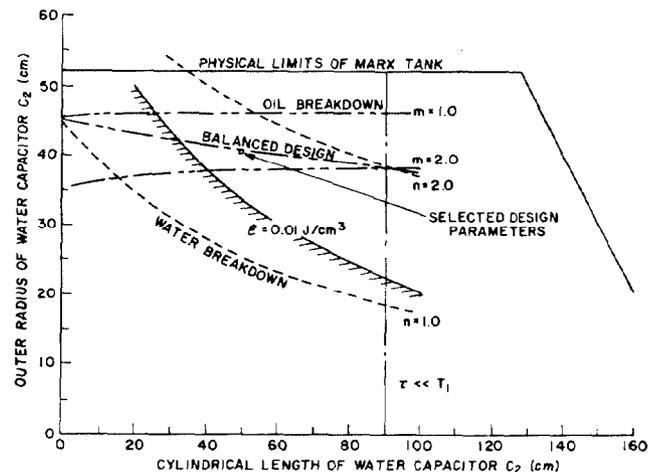


Figure 7. Constraints affecting the physical dimensioning of the output filter.

Preliminary Diode Study

Prior to the assembly of the VEBA short-pulse mode, a short series of long-pulse diode experiments were completed by attaching the diode assembly directly to the Marx. To obtain a variable pulse duration, the Marx output was "crow-barred" by an over-volted oil switch mounted in the Marx tank. Using this circuit, a pulsed voltage of approximately 800 kV could be applied to the magnetized injection diode which would later be used in the initial short-pulse microwave experimentation.

Although the results of these experiments were preliminary, they did show that the diode closure rate in the foil-less geometry was slower than that experienced in a conventional geometry, which included an anode foil. With an anode-cathode separation of 4.4 cm and an applied magnetic field of 10 kG, the diode did not transition to a short until 2.6 μ sec after the voltage had first been applied. This would indicate a closure rate of approximately 1.7 cm/ μ sec, a result which is consistent with the earlier observations of Friedman and Ury.⁷

Acknowledgements

The mechanical design of the VEBA was done by T. J. O'Connell, M. Jevnager and R. E. Lanham. Useful discussions concerning the design were held with J. D. Shipman, Jr. and J. K. Burton.

References

1. V. L. Granatstein, P. Sprangle, R. K. Parker, and M. Herndon, "An Electron Synchrotron Maser Based on an Intense Relativistic Electron Beam," J. Appl. Phys. (to be published May 1975).
2. V. L. Granatstein, M. Herndon, R. K. Parker, and S. P. Schlesinger, "Strong Submillimeter Radiation from Intense Relativistic Electron Beams," IEEE Trans. MTT-22, No. 12, 1000 (1974).
3. J. E. Boers, "Digital-Computer Solution of Laplace's Equation Including Dielectric Interfaces and Small Floating Electrodes," Record of the 11th Symposium on Electron Ion, and Laser Beam Technology (San Francisco Press, San Francisco, 1971), p. 433. This code has been substantially modified at NRL by J. D. Shipman, Jr.
4. O. Milton, "Pulsed Flashover of Insulators in Vacuum," IEEE Trans. EI-7, No. 1, 9 (1972).
5. H. J. White, P. R. Gillette, and J. V. Lebacqz, "The Pulse Forming Network," Chap. 6 of Pulse Generators edited by G. W. Glasoe and J. V. Lebacqz, (McGraw-Hill, New York, 1948).
6. The code used for this calculation was developed at NRL by W. H. Lupton, J. P. Boris, and J. D. Shipman, Jr. A limited discussion of this code can be found in the following reference: J. K. Burton, J. J. Condon, M. D. Jevnager, W. H. Lupton, and T. J. O'Connell, "The Triton Electron Beam Accelerator," IEEE Proceedings of the Fifth Symposium on Engineering Problems of Fusion Research Conference Record (1974), p. 613.
7. M. Friedman and M. Ury, "Microsecond Duration Intense Relativistic Electron Beams," Rev. Sci. Instr. 43, 1659 (1972).