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IEEE Conference Record of the 1990 19th Power Modulator Symposium

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1990 Nineteenth Power Modulator Symposium

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FOREWORD

This Conference Record of the 1990 Nineteenth Power Modulator Symposium should once again provide an update and review of a wide range of power-modulator-related topics ranging from fundamental research and device development to systems engineering and applications. It should also continue to be a primary reference for the current state of the technologies associated with power modulators and electronics. The quality of the technical content of this year's Symposium is due primarily to the efforts and leadership of my Program Chairman, Martin Gundersen, and the Technical Program Committee. In addition to the Conference Record, Martin will also edit a special issue of the IEEE Transactions on Electron Devices that will contain selected papers from this year's Symposium.

This year's Symposium saw the introduction of several new features. A short course on "Power Modulator Components and Techniques" was held on Monday, the day prior to the start of the Symposium. Taught by Bill Nunnally and Ed Chu, the course turned out to be, literally, "standing room only."

The Keynote Session on Tuesday offered three keynote speakers, with the intent being to offer a DOE, Tri-Service, and SDIO perspective on power-modulator issues. The three presentations were, respectively, "Modulator Applications in High-Energy Accelerators," by Lou Reginato; "National Pulse Power Issues," by Steve Levy; and "SDIO Power and Power Conditioning Issues," by Mitch Nikolich.

The poster presentations were expanded to two Poster Sessions, with over fifty (50) posters presented, and the computer software swap continued, albeit with limited participation. Two student paper travel awards were presented, one to Randy Roush of Old Dominion University, and the second to Don McDonald of the State University of New York at Buffalo.

This year's Symposium also saw the introduction of the Germeshausen Award, named after Kenneth J. Germeshausen, recognizing outstanding contributions in the science and technology of power modulators and related pulse power. As the first recipient, Dr. Germeshausen's plaque read "For his seminal contributions to the development of the high power hydrogen thyratron, and the subsequent growth of the power modulator engineering community." Dr. Germeshausen's award was graciously accepted for him by Herb Grier.

My thanks again to my Technical Program Chairman, Martin Gundersen; to Mark Goldfarb and Janice Brooks of Palisades Institute for Research Services, Inc.; to Army LABCOM ET&DL, Air Force WRDC, AFWL, the Electron Devices Society of IEEE, and my own NAVSWC, for sponsorship; and to Jessica Rogers and the staff of the Hyatt Islandia, San Diego, CA.

The 1992 Twentieth Power Modulator Symposium will be held June 23-25, 1992 at the Myrtle Beach Hilton, Myrtle Beach, SC.

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THE 1990 NINETEENTH
POWER MODULATOR SYMPOSIUM

The Departments of the Air Force, Army and Navy,
The Advisory Group on Electron Devices
and
The Electron Devices Society of IEEE

Present the
Germeshausen Award

to

MR. KENNETH J. GERMESHAUSEN

For His Seminal Contributions to the Development of the
High Power Hydrogen Thyratron, and the Subsequent
Growth of the Power Modulator Engineering Community.

June 28, 1990

Lawrence H. Luessen
General Chairman

Martin Gundersen
Technical Program Chairman

Kenneth J. Germeshausen

A native of Woodland, California, Kenneth J. Germeshausen travelled east to attend college at the Massachusetts Institute of Technology. During this time he took a laboratory class from Prof. Harold Edgerton. He was graduated in 1931 with a B.S. degree in Electrical Engineering. In the thirties, during the depression, he went to work for Prof. Edgerton, applying high-speed photographic and stroboscopic techniques to study and solve industrial problems. He subsequently formed a partnership with Edgerton and another of 'Doc' Edgerton's students, Herbert Grier. The partnership eventually became EG&G, Inc.

Germeshausen and Edgerton also conducted research into the generation and measurement of short-duration, high-energy electrical pulses. Germeshausen's work proved to be basic to the development of radar modulators and firing sets for atomic weapons. He developed the high voltage hydrogen thyratron, in spite of many obstacles. He worked in these areas with both the MIT Radiation Laboratory and the Atomic Energy Commission. He has more than 50 patents covering electronic circuits, gaseous discharge tubes, and other devices. His inventions include flash lamps, hydrogen thyratrons, and gaseous discharge switch tubes.

At EG&G, he was also famous for always coming around to see how things were going. He would walk in, not say much of anything, look on a bit, then move on. It also seemed that he would always turn up when some crazy scene was in progress. He had a way of looking at some big experiment or bench full of equipment, and asking the key question that no one had thought to ask in the first place. Likewise, he could just look at something and spot the trouble, or the fundamental flaw.

Germeshausen served as Vice President and Treasurer of Edgerton, Germeshausen, & Grier, Inc. from 1947 to 1954, President from 1954 to 1965, and Chairman of the Board from 1965 to 1972. Now retired, he remains a consultant to the company. He is a Fellow and Life Member of the Institute of Electrical and Electronic Engineers as well as a Life Member Emeritus of the MIT Corporation. He is a member of the Academy of Applied Sciences and a Life Trustee of New England Aquarium. In 1969, Germeshausen was elected a Fellow of the American Academy of Arts and Sciences and, in 1973, he received the Holley Medal, awarded by the American Society of Mechanical Engineers to an individual who, "by some great and unique act of genius of an engineering nature, has accomplished a public benefit." In 1976, he was awarded an honorary Doctor of Science degree by Franklin Pierce College, New Hampshire.

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MODULATOR APPLICATIONS IN HIGH ENERGY ACCELERATORS

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INTRODUCTION

The scientist desire to probe deeper and deeper into the subnuclear structure of matter has led to the development of a remarkably sophisticated technology for high energy accelerators. Engineers have led the way in the development of the hardware which drives and controls these sophisticated accelerators. Machines such as the Fermilab Tevatron and the Stanford Linear Collider produce beams from 50 GeV to one TeV which collide and generate new subnuclear particles. During the next decade, the 20 TeV Superconducting Super Collider (SSC), will be constructed in Texas to answer some of the deepest questions of elementary particle physics. At the core of these machines is a variety of pulse generators, "modulators," which power the devices that generate the accelerating potentials.

Modulator or Pulsed Power

Modulation is defined as a "process whereby the amplitude, frequency, phase or pulse duration are modified in accordance with a message signal." Although such definition was intended for radio wave transmission it certainly is appropriate for pulse generators. A simplified representation of a modulator is shown in Fig. 1. The input power line voltage is stepped up or down, rectified, stored and then delivered to the load by means of a switch in accordance with the modulating signal or trigger.

By this definition, all accelerators are driven by "modulators." Also, it can be said that all modulators are "pulsed-power" devices. Modulators had their inception during the early days of radar and to this day their largest application is still in that field. The word modulator is almost synonymous with radar and that is perhaps why the field of "pulsed-power" was initiated in the mid sixties. During that period, the requirement to produce bright x-ray flashes led to the development of the gigawatt pulsed power devices for accelerators that generate mega-volts at mega-amps of current at very low repetition rates. There is no clear cut separation between "modulators" and "pulsed-power" devices as can be noted from the wealth of papers from both fields that are given at the Pulsed Power Conference and the Modulator Symposium. A fairly broad distinction can, however, be made if one looks at the generic properties of the two devices in terms of repetition rates (frequency), peak power and/or average power. Modulators operate at frequencies from a few hertz to many megahertz whereas pulsed-power generators are in the millihertz category; modulators deliver output peak power levels from a few kilowatts to hundreds of megawatts whereas pulsed power devices go from a few hundred megawatts to the terawatt levels; the average power levels of modulators is typically from the kilowatt to the megawatt whereas pulsed power devices are less than one kilowatt (for example a one terawatt, 100 ns device pulsing 4 times in one hour has about 100 watts of average power). There are other differences between the two devices which distinguish the modulator from the pulsed-power device. High energy accelerators throughout the country are experimental devices for physicists and are required to operate 24 hours a day. The reliability or lifetime of the modulators which drive these accelerators is measured in terms of thousands of hours at high repetition rates. This corresponds to a pulse lifetime greater than 10^{10}. The requirement for radar modulators is perhaps even more stringent whereas pulsed-power devices have pulse lifetimes measured in the few millions of shots. The difference in the life times of these pulse generators dictates the type of switch used to deliver the energy to the load. Again, this is a broad definition and considerable overlap exists but in general pulsed-power devices utilize discharge elements (switches) which are electric arcs (spark gaps) whereas modulators use gas devices (thyratrons), solid state (SCR's), and vacuum devices (gridded tubes) as switching or controlling elements. Comparatively recent developments in the switching field have made available other devices which are finding usage in both the modulators and pulse power devices. Another old technology which has undergone considerable advancement in recent years is the technique of pulse compression by means of saturable reactors. Recent developments in the field of high permeability and high saturation flux density magnetic materials coupled with existing thyratrons or solid state devices has produced modulators with extremely high peak power levels, high repetition rates and indefinitely long life.

Modulators for Particle Accelerators

In any accelerator, a potential difference must exist between two points to impart an energy QV to the particle of charge Q. This potential is always generated by a modulator either "directly" or "indirectly." In the vast majority of high energy accelerators the potential difference is generated "indirectly" by a modulator which powers a radio frequency device such as a klystron or a gridded power tube. Someone unfamiliar with rf accelerators might question how a charged particle (electron, proton, heavy ion) gains energy in a sinusoidal electric field. The acceleration is simply achieved by arranging the electric field so that the particle either rides the crest of the wave or it is in a field free region when the decelerating field is present. Figure 2 shows a simplified rf linac drive system. The modulator delivers a pulse voltage to the rf device which generates a rf voltage between points A and B. The particle is accelerated from A to B but is in a field free region (drifts) from B to A during the opposing potential. The drift tubes are made shorter as the particle gains energy.

As previously mentioned, most of the high energy accelerators such as SLAC, Fermilab and now the SSC obtain the high energy (GeV to TeV) by utilizing rf drivers. There is another accelerating scheme which is considered low energy in terms of total voltage gain (hundreds of MeV) but one which can accelerate electron beams of very high currents (tens of 10 kA). This scheme, the induction accelerator, was pioneered by Nicholas Christofilos in the early sixties at LLNL and has resulted in a number of accelerators from the Astron to the Advanced Test Accelerator (ATA). In an induction accelerator, the potential is applied across a gap "directly" from a modulator. The amount of beam current which can be accelerated, is, therefore, limited only by the drive impedance of the modulator. Figure 3 shows the basic principle of the induction accelerator drive system. The voltage V appears at each gap induced by a one turn loop around a ferromagnetic core. Hundreds of these induction cells can be bolted together to produce the desired accelerating potential with no external fields. These accelerators, although considerably less sophisticated than the rf ones, have been useful in a number of experimental programs such as free electron lasers, beam propagation and food irradiation.

Currently on assignment with the Lawrence Berkeley Laboratory and the Superconducting Super Collider (SSC). This work was supported by the Director, Office of Energy Research, Office of Fusion Energy of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Hard-tube, line-type or magnetic modulator

The application usually determines the type of modulator which is selected to achieve the desired parameters. In high energy rf accelerators as well as induction types, one or more of the three basic types of modulators have been utilized to generate the acceleration voltages. The Heavy Ion Linear Accelerator (HILAC), a drift-tube Linac at LBL, has used hard-tube modulators to power the gridded rf tubes (Fig. 4).

The Astron used a hard-tube modulator to charge and regulate the voltage on the line-type of thyratron switched modulator, thus powering the induction cells "directly" (Fig. 5). The Stanford Linear Accelerator (SLAC) uses a thyratron switched line-type modulator to drive the klystrons (Fig. 6). The Advanced Test Accelerator (ATA) has used a thyratron modulator to charge and regulate the spark-gap switched line-type of modulator (Fig. 7). The Fermi National Accelerator Laboratory (FNAL) uses SCR charged and SCR switched line type of modulators to power the klystrons.

Figure 8 shows simplified schematics of the three basic types of modulators. Although thyratrons are shown as the switching element in Fig. 8(b) and SCR's in Fig. 8(c), the actual switch selected will be tailored to the application. High power hard-tube modulators typically employ gridded power tubes as the pulse generating element. The modulator consists of a power supply with capacitive energy storage and a hard tube controlled by the modulating signal (Fig. 8(a)). This type of modulator is without a doubt the most versatile but also the least efficient and most costly. Versatility is achieved simply because the quasi-linear switching tube can control the rise time, pulse width and flat top of the pulse. This type of modulator does not require a regulated power supply because the output pulse can be controlled by adjusting the grid drive signal in a feedback loop. That is, by comparing the output pulse to the desired modulating input signal, a correction signal is generated which adjusts the drive signal to achieve the desired output. This type of modulator can generate any pulse duration and can be used as an opening switch under load fault condition. Another advantage of the hard-tube modulator is the fact that in a feedback loop it can be used to maintain set voltages or currents under varying load conditions. In lower power modulators, solid state devices such as MOSFETS and transistors provide the same function as the hard-tube device. Step-up transformers are rarely used in conjunction with hard-tube modulators because the bandwidth of the device (low and high frequency) can be compromised by the limitations of the transformer. Hard tube modulators are generally used when the following parameters are desired: high degree of regulation, output voltages less than 100 kV, several hundred amperes and pulse duration in the tens of milliseconds.

The thyratron switched modulator of Fig. 8(b) shows the basic concept of the "line-type." The first thyratron resonantly charges the Pulse Forming Network (PFN) while the second thyratron discharges the PFN into the load. Voltage regulation is either provided by the power supply or by a switching device with dequing. This type of modulator is by far the most popular.

The Stanford Linear Accelerator uses 240 line-type modulators with a 15 to 1 step-up transformer at the output to power the Klystrons which generate a 3.7 µs rf pulse of 2856 MHz, thus accelerating the electrons and positrons to 32 GeV. This modulator delivers a 24 kV pulse to the transformer input for a peak power of 150 MW at repetition rates of up to 360 Hz (Fig. 6). The line-type modulator is the simplest and least costly and in most cases satisfies the drive requirements for high energy accelerators. The output pulse is initiated by a trigger to the thyratron after the PFN has been charged; the output pulse terminates once all the energy in the PFN has been delivered to the load and the thyratron stops conducting. Typically the PFN impedance is matched to the load (through a transformer if necessary) so that one half the PFN voltage is delivered to the load. This type of modulator cannot control the output voltage pulse if the load impedance varies. If the load impedance variations are not excessive, output voltage control is obtained by a "matching network" either at the load or at the switch output. If the energy storage in the PFN is damaging to the load (klystron) under fault conditions, a crowbar is used to divert the energy and protect the rf device from permanent damage.

A third type of modulator which is being used to drive induction accelerators is the hybrid "magnetic-line-type" shown on Fig. 8(c). In this type of modulator the charging pulse is initiated by either a solid state device or a thyratron and is then compressed in time achieving higher peak power; the PFN is charged in the compression process and the energy is discharged by the output saturable reactor. The pulse duration is determined by the PFN while the rise time is dependent on the load and magnetic switch properties. The magnetic modulator technology is more complex, less efficient and certainly more costly than the line-type but in some specific applications it may be the only viable solution.

The following discussion, hopefully, will shed some light on the merits and disadvantages of the magnetic modulator. The increase in complexity is quite obvious simply by looking at the number of compression stages that are used after the compression process is initiated by a switching device. It is also evident that each saturable reactor must be reset to the exact initial magnetic flux density (B_i) to avoid pulse to pulse jiter. The DC power supply regulation required is directly proportional to the number of stages used. In a resonant charger, the pulse compression occurs at the point in time when $B_s - B_i = 1/AN\int V_o(1\text{-}\mathrm{Cos}wt)\,dt$. One can see from this equation how the time when saturation occurs is affected by changes in V_o and B_i. For example, if one tries to maintain a jitter of ± 2.5 ns and the initial charging time is 5 µs, the voltage regulation must be maintained at ± 0.1% which is not difficult for most power supplies. Changes in B_s due to temperature or other effects were ignored.

The lower efficiency of a magnetic modulator comes about because the saturable reactor is basically a leaky switch. The saturable reactor is leaky due to the shunt combination of the unsaturated inductance and the eddy current losses. This leakage impedance is a function of geometry and core material properties. In most magnetic modulator systems the majority of the losses can be attributed to the final stage of compression because this is where the dB/dt is the highest.

In any switch, the ratio of the "off" impedance to the "on" impedance (Z_{off}/Z_{on}) should be at least ten. The leaky properties of a magnetic switch coupled to the requirement that in order to efficiently charge the PFN (Fig. 8(c)) the source impedance should be an order of magnitude lower, forces the magnetic modulator to be a low impedance device. This type of modulator couples nicely to high current induction accelerators but is a mismatch for rf devices (Klystrons) unless a large number of them are driven in parallel. A good match, however, can usually be obtained by designing the magnetic modulator to deliver the desired energy per pulse through a step-up transformer to the particular rf device.

From the previous discussion it would appear that magnetic modulators are more complex, less efficient and cost more than the conventional line-type. Why then have they been used extensively in induction accelerators, magnetron drivers and lasers? The answer to that can be the following: "There are modulator requirements where no conventional switch currently exists which can deliver the peak power, di/dt, repetition rates and the lifetime of the magnetic modulator." The magnetic pulse compression process, once initiated, consist of passive devices which do not wear out. It is possible, therefore, to design a magnetic modulator so that the switch which initiates the process can be utilized at its most efficient operating point achieving reliability and practically unlimited life. The selection of the initial switch will be determined by the energy per pulse, repetition rate, lifetime, economics and somewhat by the engineer's preference.

The Experimental Test Accelerator (ETAII) required a one kilojoule, 150 kV, 70 µs modulator capable of 5 kHz. Thyratrons were chosen to do the pulse charging and switching coupled to three compression stages and one step-up transformer (Fig. 9). Since switch longevity was not a strict requirement, thyratrons were chosen because they could operate at higher di/dt and higher voltages than SCR's, thus reducing the number of stages and the number of step-up transformers. In cases where the pulse energy is less and the switch's lifetime needs to be greater than 10,000 hours, the engineer may choose a solid state switch (SCR) thus he must increase the number of stages to achieve the desired output pulse still maintaining a di/dt which is within the ratings.

SUMMARY

In the broad definition of modulator, spark gaps were not considered to be a switching element which is applied frequently. Spark gaps are, however, the simplest, most efficient, highest peak power, highest di/dt and highest compression gain switch available and at low repetition rates they may be the switch of choice. Modulators have always required long life (billions of pulses) at high repetition rates and one of the three basic types have offered the optimum solution to most requirements. Of the three, hard-tube, line-type, magnetic, the engineer should choose the simplest that will satisfy his requirements. From a system viewpoint it should be every engineer's goal to minimize the number of times that he handles the power starting with the 60 Hz line no matter which type of modulator is used. In high energy accelerators, specifically those which are driven by rf devices, the modulator of choice has been the line-type switched by a thyratron. This type of modulator satisfies all the needed requirement to reliably drive these experimental machines for many thousands of hours at high repetition rates. In the case of induction accelerators which are high current devices (low impedance) and are driven by modulators directly, the magnetic modulator may be the only choice if high repetition rates are required. Modulators certainly are the "heartbeat" of high energy accelerators and outside of the field of radar, they are the most widely used in generating high power pulses.

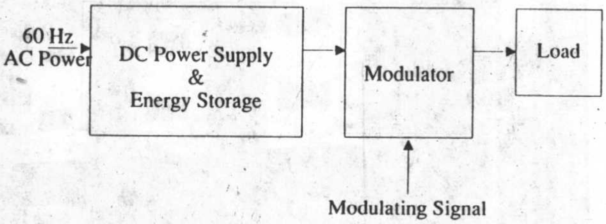

Fig. 1 Simplified Block Diagram of a Modulator.

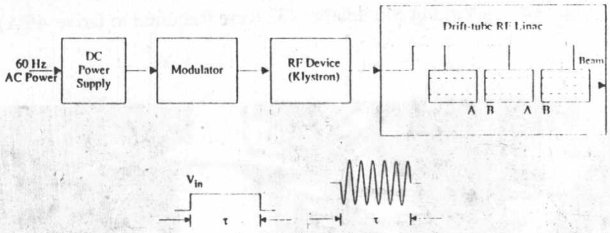

Fig. 2 High Energy Accelerating Structure Indirectly Driven by a Modulator.

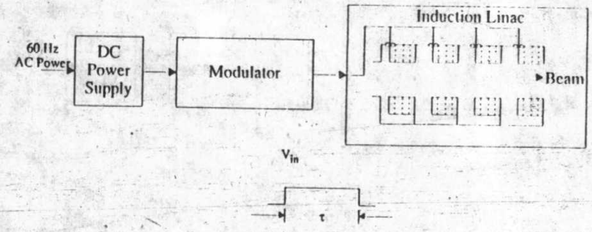

Fig. 3 Inductor Accelerator Cell Directly Driven by a Modulator.

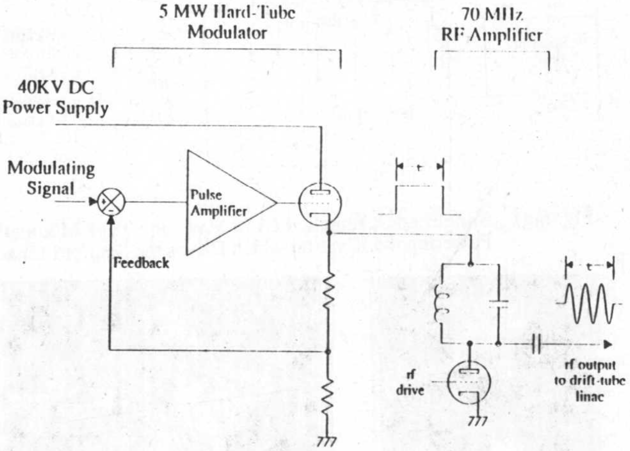

Fig. 4 Simplified Schematic of 5 MW Hard-Tube Modulator/ Regulator Powering a RF Amplifier which Drives a Drift-Tube RF Linac, the HILAC.

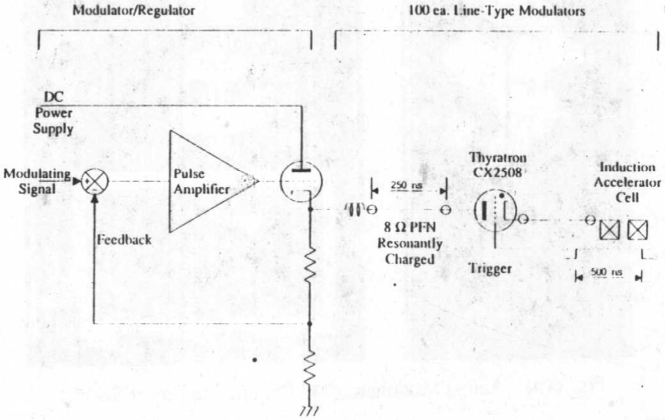

Fig. 5(a) Simplified Schematic of 10 MW Hard-Tube Modulator/Regulator Charging one of 100 Thyratron Switched Line-Type Modulator for Driving Astron.

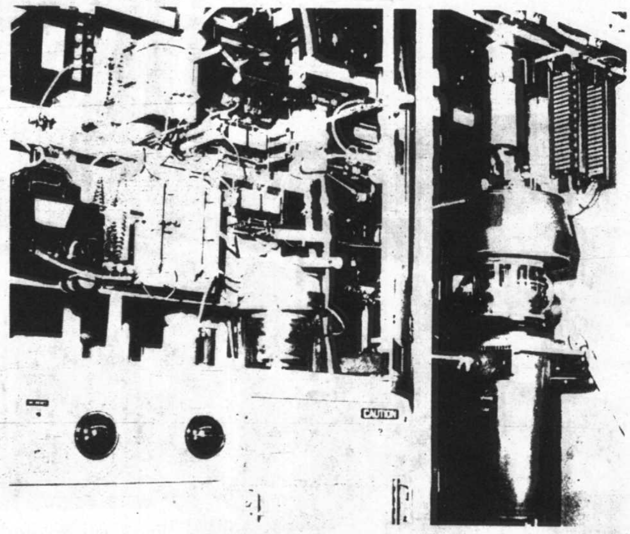

Fig. 5(b) Actual Modulator - 5 total charged 500 Line-Modulators.

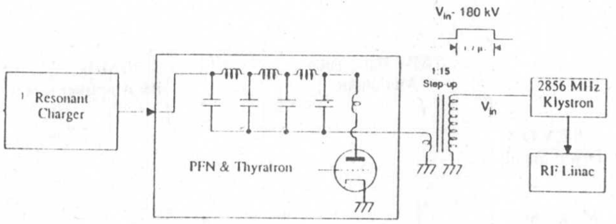

Fig. 6(a) Simplified Schematic of 150 MW Line-Type Modulator Powering the Klystron which Drives the Stanford Linac

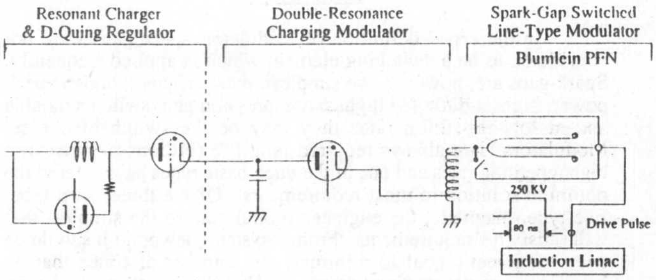

Fig. 7(a) Simplified Schematic of 5 GW Thyratron Charged and Spark-Gap Switched Line-Type (Blumlein) Modulator Driving the ATA Induction Linac Directly.

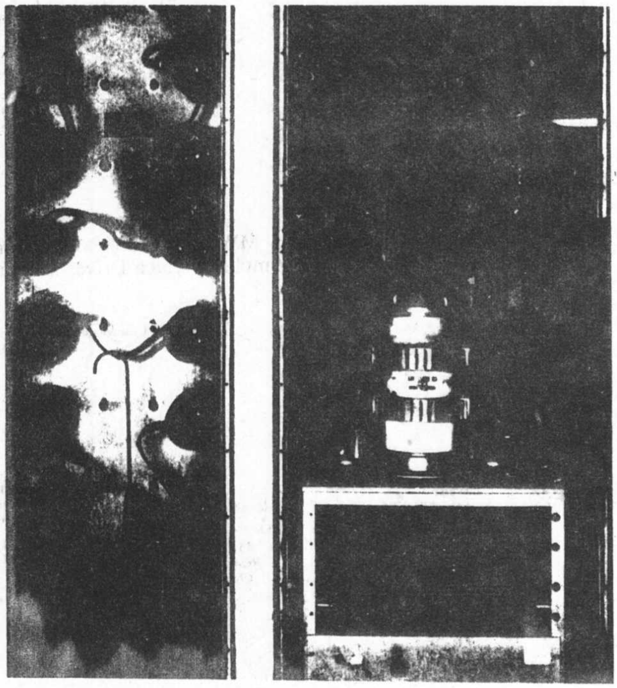

Fig. 6(b) Actual Modulator (240 Required to Power SLAC).

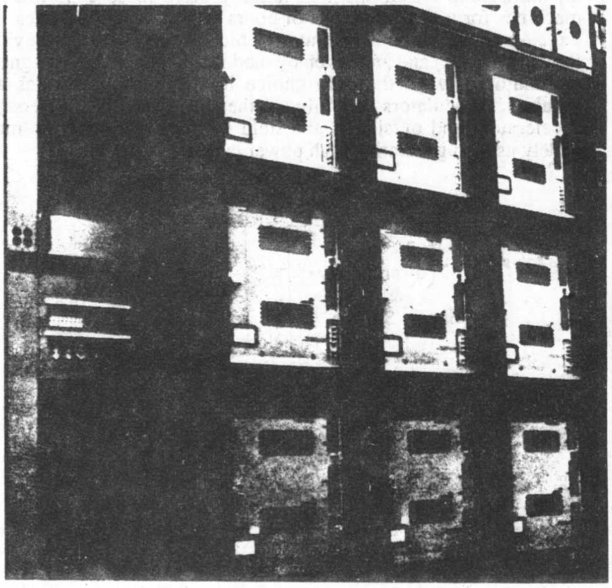

Fig. 7(b) Charging Modulator (232 were Required to Drive ATA)

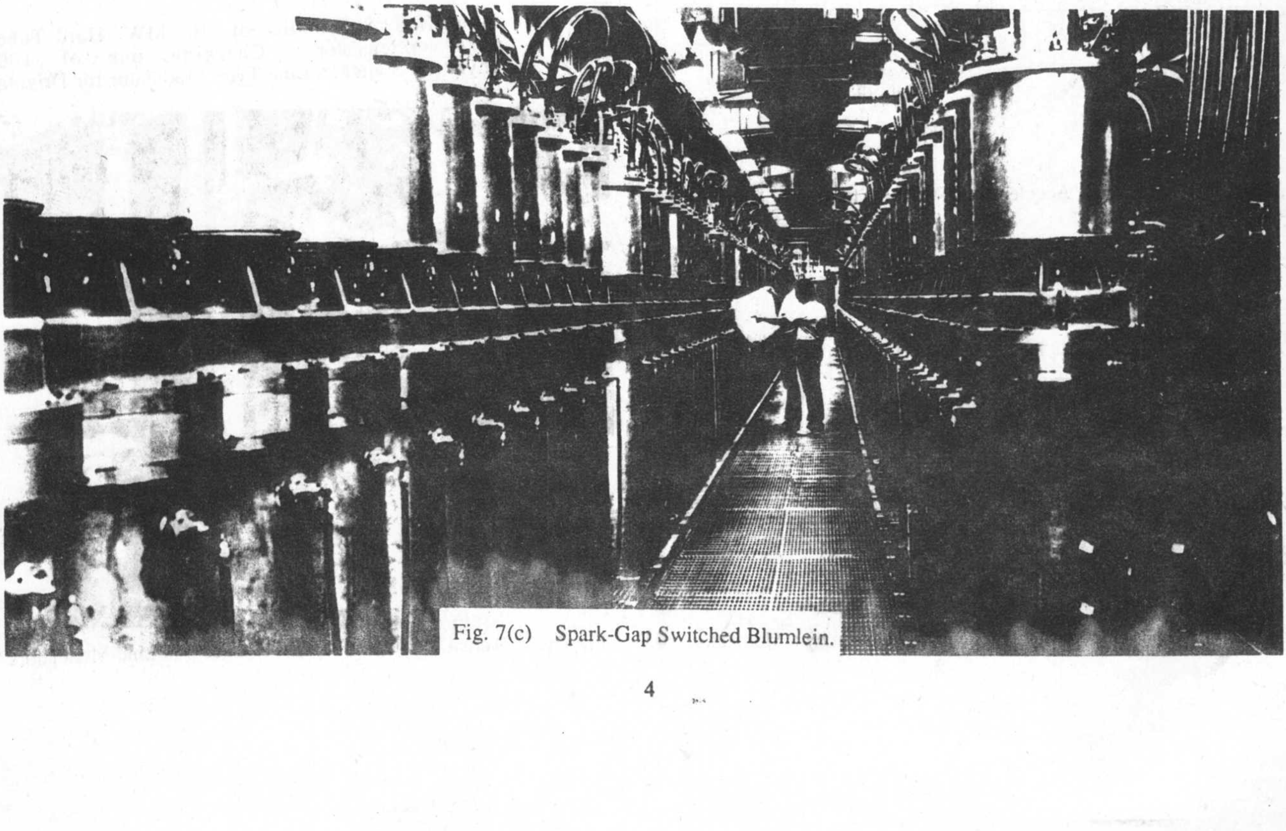

Fig. 7(c) Spark-Gap Switched Blumlein.

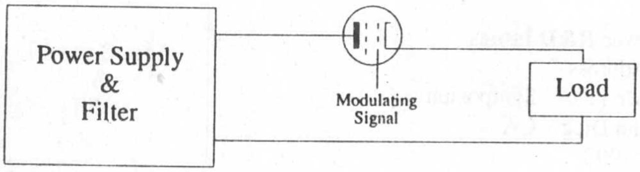

Fig. 8(a) Hard-Tube Modulator (For Low Power Solid State Devices such as MOSFETS Repalce the Tube)

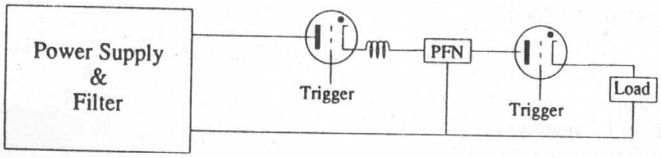

Fig. 8(b) Line-Type Modulator (Switch can be a Thyratron or SCR)

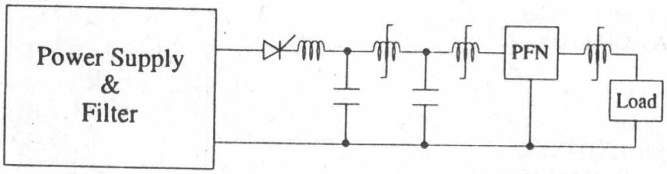

Fig. 8(c) Magnetic Modulator (Switch usually a SCR but can be Thyratron)

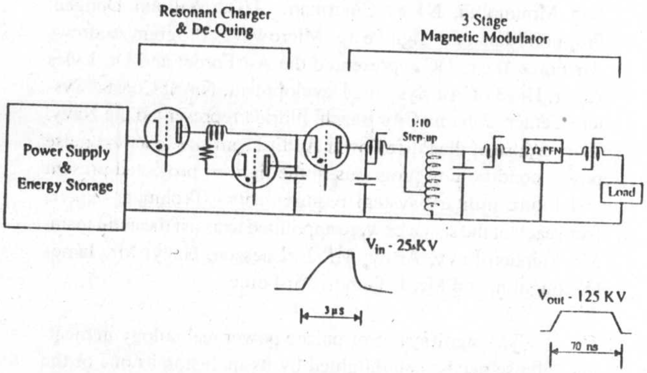

Fig. 9(a) Simplified Schematic of a Thyratron Switched Magnetic Modulator for ETA II

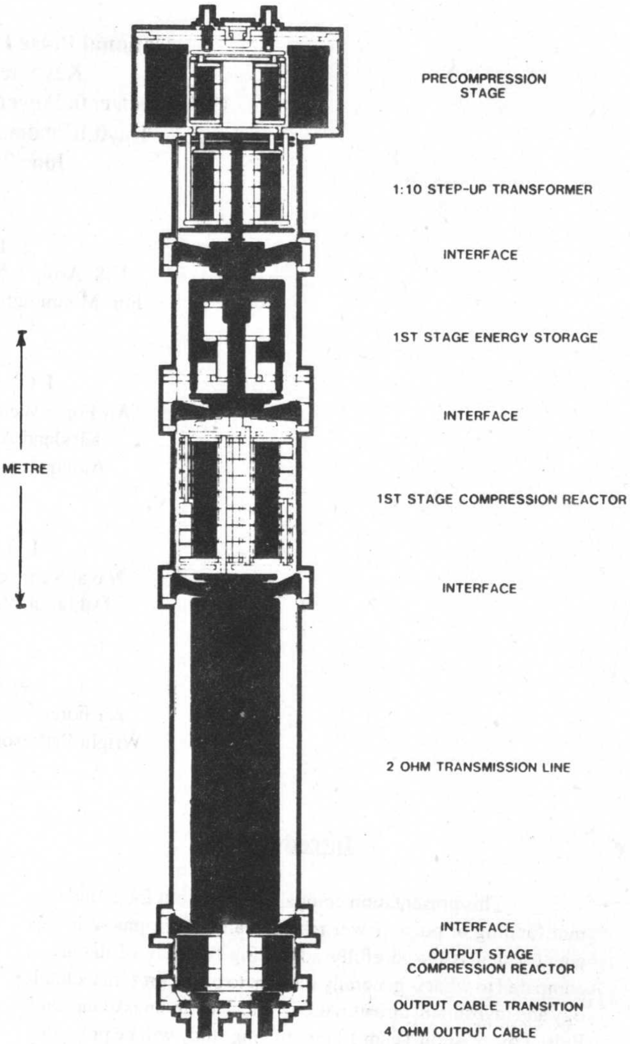

Fig. 9(b) Cross Section of Magnetic Modulator.

National Pulse Power R&D Issues

Keynote Address
1990 Nineteenth Power Modulator Symposium
Haytt Islandia, San Diego, CA
June 26, 1990

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Introduction

This presentation compares the present focus and current funding of pulse power research and development in this country that is purposefully advancing the state-of-the-art as compared to what is generally thought to be the present technology and investment thrusts nationwide. The findings of the DoD Pulse Power Audit Team 18 month long study will be presented for the years FY89 and 90 so that we can understand the relationship between pulse power technology products and the investments that are being made to foster those R&D products. We will compare the findings with those published in the Congressional Critical Technologies Report and compare the results of each. Finally we will identify the needs that are not being satisfied according to the DoD key technologists involved in the audit study and offer some suggestions on what can be done to meet those needs.

An important national defense requirement is the development and fielding of advanced, high-power weaponry (electric guns, high power microwave, lasers, particle beams), along with other systems of interest such as electric propulsion. These weapons and systems are dependent to a great extent upon the availability of high-energy, pulse power components - capacitors, switches, inductors, batteries, generators/pulsed alternators. There was a perception at the highest levels within DoD that pulse power was becoming an important technology to the military and that there should be an assessment of investments and the direction of the work to determine as whether the technology programs were on target or needed some changes. Consequently a Tri-Service Team was formed in November 1988 under the auspices of the Joint Directors of Laboratories with Dr. C. G. Thornton, Director, U.S. Army Laboratory Command Electronics Technology and Devices Laboratory, Fort Monmouth, NJ as Chairman. LTC William Dungan, Program Manager, High Power Microwaves Program Andrews Air Force Base, DC represented the Air Force; and Dr. Lyles Adair, Head of Air Systems Development, Naval Coastal System Center, Panama City Beach, Florida represented the Navy. The purpose of the Pulse Power Audit Team was to assess pulse power conditioning programs in the light of projected present and future military system requirements. Technical experts from each of the services were appointed to assist the audit team; Mr. Stephen Levy, Army; Mr. L. Luessen, Navy; Mr. James O'Loughlin, and Mr. J. Turner, Air Force.

The significance of pulsed power technology in meeting defense needs is highlighted by its inclusion as one of the critical technologies in the 1989, 90 Department of Defense Critical Technologies Plans for the Committees on Armed Services, United States Congress provided each March 15th. In the 1989 plan it was stated that the total S&T funding for pulse power in FY90 is in the order of $65 million, most of it from SDIO. However, when the Plan was reviewed in depth it was found that differences exist in the interpretation of component research and development, and in the developmental status and availability of components for systems applications.

Study Procedures/Actions

It was obvious at the beginning of the study that limited, credible data was not available on the magnitude and scope of pulse power component research and development in the United States. For example, one of the initial results of the study was that only 1/4 to 1/3 of the overall S&T funding for pulse power components and sub-systems is being invested in R&D and that DoD and DoE provide relatively little funding for basic research. It was also determined that there was no central or single group within DoD that could provide complete and accurate data on the level of R&D investment and the products of those investments on a coherent, national scale. There was a perception in the defense community - that turned out to be accurate - that systems demonstrators were not advancing the state-of-the-art of critical pulse power components to the degree required for field operation. There was also a perception - not completely accurate - that there was not a sufficient level of Tri-Service cooperation. Actually, our study verified that there was a high level of coordination and joint programs within the DoD community.

The Pulse Power Audit Team developed and carried out the following actions listed in TABLE 1:

TABLE 1: PULSE POWER TEAM ACTIONS

- Surveyed Efforts and Resources Used in Advanced R&D by:
    - -Tri-Services, SDIO, DARPA, DoE,
    - -National Laboratories, Industry, Universities
- Reviewed Facilities Engaged in Pulse Power R&D
- Assessed Foreign Technology
- Established Technology Status and Direction
- Provided Inputs to DoD Critical Technologies Plan
- Identified Promising Areas for R&D
- Addressed Expanded Joint Service Opportunities

The Pulse Power Audit Team did not address weapons/system demonstrators, simulators (EMP, EMR), or a survey of off-the-shelf purchased pulse power components.

Survey Breakdown

Questionnaires were sent to government and non-government organizations that are known to have an active involvement or interest in pulse power component and pulse power conditioning technology based on the personal knowledge of the members of the Pulse Power Audit Team and the Team's supporting technologists, reinforced by referrals from various contacts. Only funds that are directed towards the advancement of pulse power technology were tracked, as separate and distinct from those funds associated with the development of systems using pulse power components, the construction of facilities or the demonstration of systems using outright purchases of off-the-shelf technology. A major difficulty was tracing the funding from its source to the ultimated user, and insuring that acquired data was not duplicated.

TABLE 2: TECHNICAL AREAS SURVEYED

- Energy Storage
    - -Capacitors, Pulsed Batteries, Inductors
- Rotating Pulsed Machines
- Switching
    - -Solid-State, Non-Solid-State, Explosive
- Magnetic Components
- Pulsed Power Circuits
- Materials
    - -Insulators, Dielectrics, Superconductors
- Applications

TABLE 3 lists the number of organizations sent survey forms and the organizations that responded to the survey questionnaire. The organizations that responded were contacted where there was a question as to whether the funding contributed to the advancement of the state-of-the-art. In the actual distributed form we asked each organization to describe the type of work they were reporting and information on their sources of funding.

TABLE 3: ORGANIZATIONS SURVEYED BY AUDIT TEAM

Agency/Group	No. Surveyed	Organizations Responding
DOD	10	•ETDL, BRL, BRDEC, NSWC, NRL, WRDC, AFWL, AFATL, DNA
DoE/Nat'l Labs	4	•Sandia, Lawrence Livermore, Los Alamos, Idaho National Labs
Industry	8	•Maxwell Labs, Physics International, Westinghouse FMC and ITT
Universities	9	•Univ. of Southern Calif., Univ. of Texas, (Austin, Arlington), Texas Tech, Auburn, Old Dominion, Univ. of Buffalo

Survey Results

Based on the results of the survey, the funds actually spent in FY 89 and 90 or specifically earmarked for research and development of advanced pulse power components and associated peripherals are summarized in TABLE 4.

TABLE 4: EXPENDITURES BY TECHNOLOGY

	FY89	FY90		
COMPONENT	DoD	Other	DoD	Other
Capacitors	$4.6M	$4.4M	$4.4M	$1.6M
Inductors	1.2	3.2	0.4	3.3
Batteries	2.5	0	1.2	0
Solid-State Switches	1.9	1.3	3.2	1.5
Other Switches	1.6	2.5	1.3	4.4
Pulse Power Circuits	2.2	1.9	1.5	2.6
Magnetic Components	0	1.0	0	1.2
Superconductors	0	0.2	0.1	0.5
Dielectrics	0.3	1.1	0.3	1.2
Rotating Pulsed Machines	0.7	7.0	0.3	2.8
Totals	**15.0**	**22.6**	**12.7**	**19.1**
Totals (DoD & Other)	**37.6**		**31.8**	

It is most important to note that the FY90 total of $31.8M is less than half the $65M listed as S&T funding forecasted for FY90 in the 1989 DoD Critical Technologies Plan; a figure that has been quoted as resources devoted to high energy/high power pulse power component research and development. The $65M amount includes money spent or planned for system demonstrators associated with pulse power and the purchase of off-the-shelf components which accounts for the discrepancy. The 1990 Critical Technologies Plan quotes an S&T funding for pulsed power as $640 million for FY 86-90. This figure was derived from the DoD and DoE programs contained in their respective budgets. The 1990 pulsed power technology write-up contains some of the systems using pulse power making the distinction between the Audit Study and the figures quoted in the present DoD Critical Technologies Plan impossible to compare except in a gross way. The explanation contained in the Plan that the figures quoted were within an order of magnitude estimates and were not to be construed as precise budgetary quantities.

Expenditures by the organization performing the pulse power component research and development are given in TABLE 5 and the organizations that are source of funds are listed in TABLE 6.

TABLE 5:
EXPENDITURES BY PERFORMING ORGANIZATION

	FY89	FY90
DoD		
Army	$2.3M	$5.1M
Navy	2.1	1.7
Air Force	6.2	4.1
Defense Nuclear Agency	4.4	3.5
DoE National Labs	4.4	5.6
Industry	6.9	5.7
Universities	7.3	5.3
(Univ. of Texas, $5.1M (FY89, $3.3M FY90))		
(other, $2.2M (FY89), $3.0M (FY90))		
TOTAL	**36.2**	**29.3**

TABLE 6: FUNDING BY SOURCE ORGANIZATION

	FY89	FY90
DoD		
Army	$5.0M	$5.1M
Navy	2.1	1.7
Air Force	2.1	3.3
Strategic Defense Initiative Office	6.7	4.2
Defense Nuclear Agency	4.4	3.5
Defense Advanced Projects Agency	2.1	1.5
DoE National Labs	4.0	4.0
Universities	0.1	0.4
TOTAL	**26.5**	**23.7**

The difference in the total funding in the two tables is believed to be related to the R&D investment data received from private industry. Discrepancies were found when the data contained in the returned survey questionnaires were compared with industry IR&D programmed annual funding and annual stockholders reports. It is the opinion of the audit teams members that private industries own investment in pulse power component research and development is relatively insignificant.

In order to provide a perspective of funding over a period of time, the normalized funding profile chart shown in FIGURE 1 was developed. Note that funding for the last five years has leveled off and remained within a modest range, with indication of a downward trend.

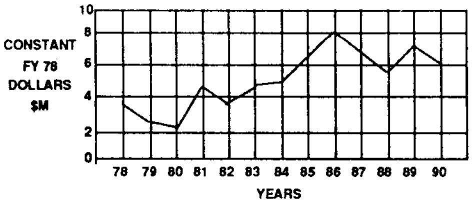

FIGURE 1: TRI-SERVICE FUNDING IN PULSE POWER R&D (FY78-90)

There is essentially no 6.1 funding support for pulse power component or pulse power conditioning R&D. Conversations with the individual service research managers has less than $1.7M out of a total of $535M (0.3%) invested in FY89 by the Army Research Office, the Office of Naval Research, and the Air Force Office of Scientific Research. Both funding and the number of a small handful of programs are expected to further diminish in FY90. Only three universities in the United States have applicable research and development program above $350,000.

Pulsed Power Technology R&D

On several occasions the Tri-Service technical members of the Audit Team discussed key technology issues from an overall perspective. One conclusion of the group was that switches, energy storage (capacitors, batteries, inductors), pulsed power conditioning circuits, and pulsed prime power, constituted the key technologies. This rather obvious conclusion is more significant in the fact that no relatively unknown technology was forecasted to be a key player. TABLE 7 contains a ranked listing of technology requirements that DoD supports. In TABLE 7 the ranking is shown by the use of different type styles. The bold elements are the most important and should be the first ranked for funding increases as judged by the tri-service technologists. The italicized elements are thought to be second ranked for increased effort. The strike through elements are considered to presently have a sufficient level of effort.

TABLE 7: TECHNOLOGY REQUIREMENTS FUNDING PROFILE

Switches

New Solid-State and Optical Switches
  - optically triggered
  - junction devices (diodes, thyristors)
Back Lighted Thyratron/ Pseudo Spark
Thyratrons
Magnetic Switches
~~Ignitrons~~
~~Crossatrons~~
~~Explosive Switches~~
~~Spark Gaps~~
~~Varistors~~