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The Klystron:
A Microwave Source of Surprising Range and Endurance*

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Abstract

This year marks the 60th anniversary of the birth of the klystron at Stanford University. The tube was the first practical source of microwaves and its invention initiated a search for increasingly more powerful sources, which continues to this day. This paper reviews the scientific uses of the klystron and outlines its operating principles. The history of the device is traced, from its scientific beginnings, to its role in WWII and the Cold War, and to its current resurgence as the key component in a major accelerator project. Finally, the paper describes the development of a modular klystron, which may someday power future accelerators at millimeter wavelengths.

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I. INTRODUCTION

Klystron designers have always maintained a close relationship to physicists, and the Plasma Physics community in particular. High-power CW klystrons at C-band and X-band have been in use for low hybrid heating in tokamacs for some time. In High Energy Physics, experimental physicists using particle accelerators rely on klystrons for increasingly higher power and frequency,[1] since the limit has yet to be reached for the energy density attainable in e+e- linear colliders. Proton colliders, such as the APT, currently under study at Los Alamos to transmute isotopes of helium and lithium into tritium, require hundreds of huge megawatt CW klystrons.[2]

There are also connections of a second and third kind with plasma physics: The study of plasmas has given rise to an intense computer code development activity and klystron engineers have been among the beneficiaries. Cold testing of cavities and other klystron components, which a decade ago required expensive model building, is now carried out on computers, with better accuracy and flexibility. Even more importantly, 2-D and 3-D particle-in-cell codes are now available to predict klystron performance without actually building them.[3] The codes are becoming increasingly accurate as computer capacity increases and programming is improved. They have been a very significant new tool in designing the state-of-the-art klystrons that will be described later.

The third connection results from a migration of plasma physicists into the microwave engineering profession, which has been taking place over the last fifteen years. It has been a consequence of the Star Wars programs and has created a more or less separate community of experimenters, with an agenda that includes the generation of gigawatt microwave pulses and the study of plasmas in microwave tubes. The new community has taken the name "High Power Microwaves" or "HPM." At this writing, microwave tube engineers and HPM physicists have yet to join forces, or reconcile differences in their respective methods.

Other scientific klystron applications are on the horizon. Radio astronomers may use klystrons to explore the surface of distant planetary bodies, such as the Europa moon of Jupiter. Europa is suspected of having liquid water under a layer of ice. If this is true, there may be life there. Europa made big news after the Galileo imager found what looked like ice blocks cracked and floating over liquid. In this case, a very stable and powerful UHF CW amplifier is needed to transmit a signal from a 150-foot antenna at Stanford to Europa and back to a 1000-foot receiving antenna at Arecibo, Puerto Rico, or to the NASA 70m dish at Goldstone, California.[4]

From the foregoing, it is clear that the klystron has impeccable scientific credentials. Before outlining its history, it is useful to sketch out the operating principles of the device.

II. OPERATION

The klystron was the first embodiment of the velocity modulation principle. The so-called Applegate diagram (Fig. 1) best illustrates this.[5] After being

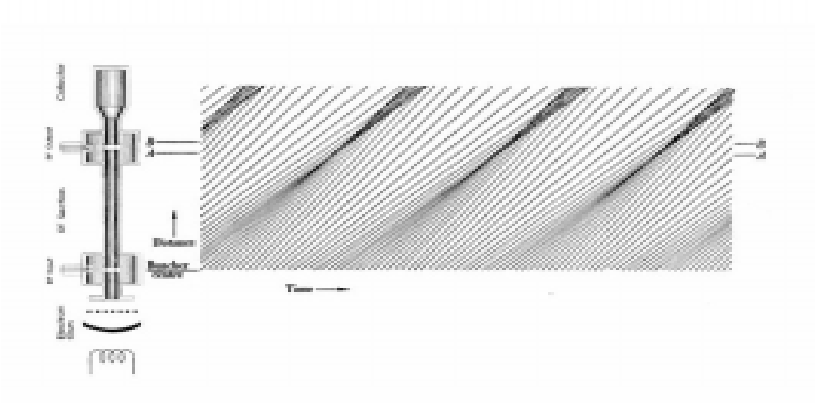


Fig. 1 Two-cavity Klystron with Applegate Diagram

accelerated by a DC voltage, electrons from the cathode initially drift with constant velocity. When they traverse a pair of closely spaced grids, their velocity is modulated by a sinusoidal rf signal. (The illustration actually shows gridless gaps, which are used in all high-power tubes.) Following that, the electrons drift and form bunches, centered at the electrons which transited the grids at the time the rf field was zero and was increasing. The electron bunches constitute an rf current, which induces a voltage across a second pair of grids downstream. That voltage can impart additional velocity modulation to the beam. The process can be repeated by including more cavities, until considerable amplification takes place, or until the increased space charge within the bunches prevents tighter bunching. This places an upper limit on the efficiency of the device. (See Klystron Tutorial) The beam eventually traverses an output cavity which is connected to a load. That cavity is designed so that the voltage induced across it slows the beam down. In the process, the electrons give up their kinetic energy to the cavity rf fields.

Klystrons are the most efficient of linear beam microwave tubes. Their efficiency increases as the space charge in the beam decreases. Beam space charge is measured by a quantity called "perveance," useful in the design of electron guns, and defined as the ratio of the beam current to the 3/2-power of the voltage. For most klystrons, the perveance chosen is between $0.5X10^{-6}$ and $2.5x10^{-6}$, but in certain cases, lower perveances may be useful, despite the higher beam voltages that they imply. The gain of multi-cavity klystrons is very high. Gains of 60 dB, or even higher, are not unusual. On the other hand, klystrons are narrow-band devices, compared with travelling-wave tubes.[6] For most applications, including communications, this is not a serious disadvantage because some klystron broadbanding is possible, at the expense of gain. However, for many radar applications and for electronic countermeasures (against radar), only TWTs are suitable. In addition to the TWT competition, low-power klystrons, particularly reflex oscillators,[7] lost the battle to solid-state replacements in radar and communication equipment some time ago.

III. HISTORY

The fundamental principle behind the klystron, velocity modulation, has an interesting history. It had its beginnings in Europe and Russia in the early 1930's. The idea was first described in a paper published in Germany in 1935, jointly authored by A. Arsenyeva-Heil and Oskar Heil titled: "A New Method for Producing Short, Undamped Electromagnetic Waves of High Intensity."[8] Oskar Heil was a peripatetic German scientist, who earned his doctorate in Physics at the University of Goettingen in 1933. There he met and eventually married Agnessa Arsenyeva, a promising young Russian physicist (Fig. 2). Together, the Heils traveled to the UK and worked with Lord Rutherford at the Cavendish Laboratory in Cambridge. Subsequently, Heil apparently joined Arsenyeva when she returned to the Leningrad Physico-Chemical Institute in the USSR. The research on velocity modulation was carried out there, although it did not result in a working device. Presumably because his wife was not allowed out of the Soviet Union again, Heil returned to the UK alone and continued his work on "coaxial-line oscillators," as the British named them, at Standard Telephone and Cables.[9] Just before World War II broke out, he slipped back into Germany without finishing his work at STC. He was apparently successful in completing development of his microwave oscillator at Standard-Lorentz in Berlin. The Germans used his tubes in WWII.

Fig. 2 Oskar and Agnessa Heil

Figure 3 shows one version of the Heil tube, which is essentially a floating drift tube oscillator with an external coaxial cavity. Cathode and collector are planar.[10]

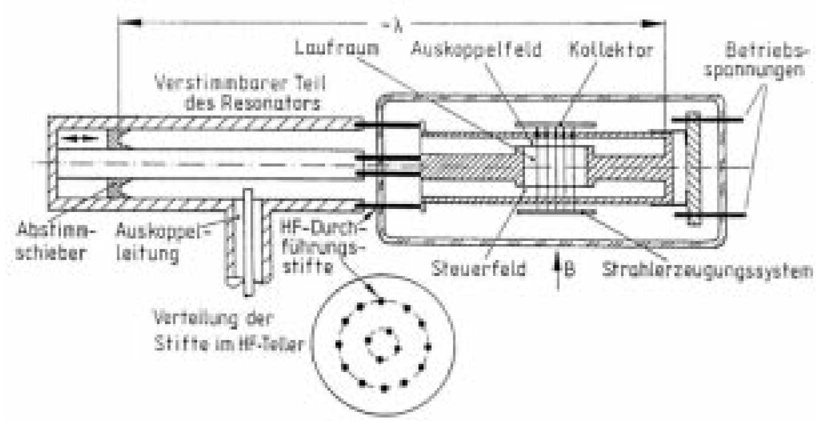


Fig 3. Heil Tube

During the same time at Stanford, W. W. Hansen, as Associate Professor Physics, was investigating "a scheme for producing high-voltage electrons," for use in X-ray spectroscopy. In the process, he invented the microwave cavity,[11] i.e. a resonator that did not depend on inductors and capacitors to store energy, and consequently was capable of developing a high voltage at high frequencies, with low losses. He also developed the theory necessary to treat resonators as circuit elements, and derived the first analytical expressions for the eigenvalues in cavities of various shapes.[12] His resonators were named "rumbatrons," (Fig. 4) presumably because of the back-and-forth travel of electromagnetic waves inside them.

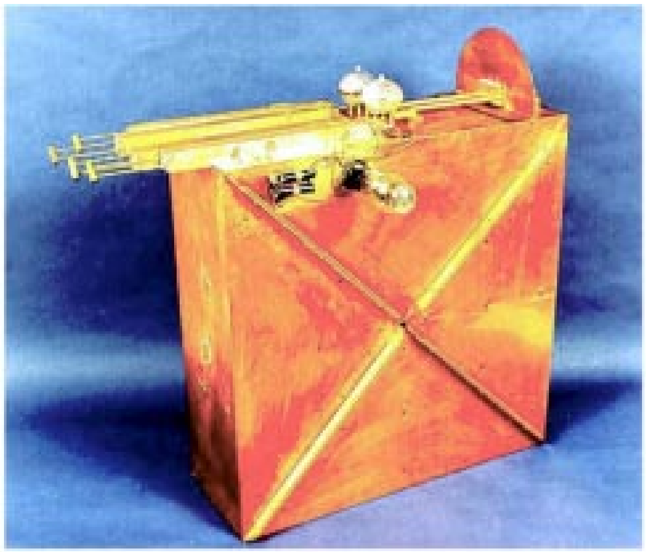


Fig. 4 The Hansen Rhumbatron

Working with Hansen at the Stanford Physics Department as Research Associates were the Varian brothers, Russell, a physicist, and Sigurd, a former barnstormer and Pan-American pilot (Fig. 5)**.** Sig Varian believed that high frequency transmitters could be used aboard airplanes to make "blind" landings possible. The missing component was a source of high-frequency power. Hansen and the Varians investigated a number of ideas, including a conical scan beam device,[13] reminiscent of the gyrocon invented much later by Budker in Russia.

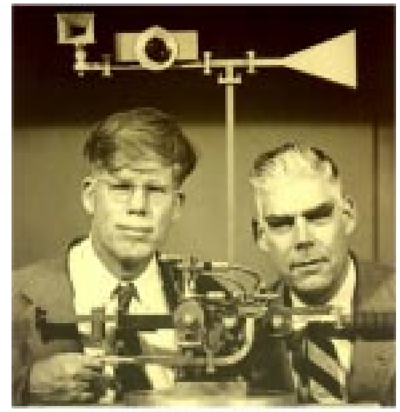


Fig. 5 Russell and Sigurd Varian

It is unlikely that they were aware of the Heils' work on velocity modulation. However, approximately two years after the Heil paper was published in Germany, Russell "had an idea in the middle of the night," in which he visualized the movement and bunching of cars at different speeds on a highway (Fig 6). This

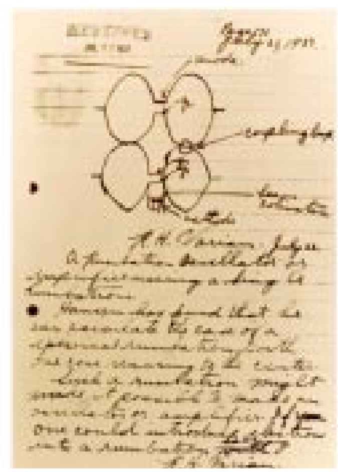


Fig. 6 A page from Russell Varian's notebook

amounted to the velocity modulation concept. Using reentrant versions of the Hansen rumbatron, the Varians constructed several successful models of a two-cavity oscillator and the modern microwave tube was born.[14] It was named "klystron" after an ancient Greek verb indicating waves washing on a shore.

The re-discovery of velocity modulation at Stanford would probably have been no more successful than Heil's initial research in Russia, except for the rumbatron. In the original Varian two-cavity oscillator (Fig. 7) grid pairs were made part of two reentrant spherical cavities. A signal was fed back from the second to the first cavity to cause the device to oscillate, since there were no microwave sources to provide rf drive to an amplifier. A patent[15] was filed in 1939 and Stanford sold the rights for the device that same year to the Sperry Gyroscope Company. Along with the patents, Sperry wisely acquired the services of the Varian brothers and their Stanford group.

Fig 7. The Varian Two-Cavity Klystron

Work on klystrons became very intensive during WWII. Radar was independently invented in Germany and Britain before the war, and was initially implemented at UHF frequencies using triodes as sources. The invention of the klystron in the US encouraged the British in a search for a higher power microwave source, one which would make possible both better target discrimination and more compact transmitters. The 1941 invention of the magnetron by Randall and Boot in Britain[16] provided such a source for radar transmitters. The same year, (and before Pearl Harbor) a visit by British scientists to America launched an extraordinary collaboration between Britain and the US, which resulted in magnetrons and klystrons being manufactured for the war effort in Western Electric, Sperry, and other American factories. The reflex version of the klystron, perfected at Sperry and in British laboratories, served as the local oscillator in superheterodyne radar receivers. Magnetrons powered the transmitters. Together, the magnetron and the klystron made possible airborne S-band radar, a major factor in securing air superiority for the RAF.[17]

Fig. 8 Hansen and Students with Disk-Loaded Waveguide

After the war, Hansen, with Ed Ginzton and Marvin Chodorow, two other Stanford faculty members, began work on an S-band accelerator at Stanford. It was based on a newly invented disk-loaded waveguide slow-wave structure,[18] which was much lighter and compact than existing lower frequency accelerators (Fig. 8). As would be the case with many others to follow, this first microwave linear accelerator required more power than was available from existing sources. Ginzton and Chodorow embarked on the design of the 20-MW klystron, a power level more than

1000 times higher than existing klystrons of the time. Recent improvements in electron beam optics, made possible by J. R. Pierce's work at Bell Labs,[19] were essential to this endeavor. Other components also had to be designed for the first time, such as high-voltage modulators and insulators, and high-power microwave windows. In 1948, the Stanford klystron for the Mark III electron accelerator, with its three cavities and wound-on beam-focusing electromagnet, eventually reached a power output of 30 MW with 1-microsecond pulses (Fig. 9).[20] It was the first

Fig. 9 The First Megawatt Klystron

multi-megawatt microwave source of any kind. In the next 50 years, there would be many more advances, but none as impressive or as widely imitated. Klystrons could now be designed to power transmitters for radar, UHF television, and space communications. They eclipsed magnetrons, because they were amplifiers, not oscillators, and because they were more powerful.

This difference between linear beam and crossed-field tubes is important and deserves a small digression. There are three generic types of microwave tubes, with the categorization based on the character of the interaction between the microwave structures used and the electron beam: Linear beam, or slow-wave tubes, are klystrons and traveling-wave tubes (TWTs). Gyrotrons and FELs are fast-wave devices. In both categories, the electron beam, after giving up part of its axial or azimuthal kinetic energy to the microwave structure, is dumped in a collector. In the third category, crossed-field tubes, (i.e. magnetrons) an electron cloud from the cathode gives up potential energy to the microwave fields, and then falls on the anode, which is the microwave structure as well. Since the dimensions of this structure must be proportional to the wavelength, the collecting area, and hence the power that can be produced, decrease as the frequency increases. Klystrons, on the other hand, can be built with arbitrarily large collectors. To the extent that a klystron beam can be transmitted through tunnel and cavities without significant interception, the ultimate output power realizable with these devices is not limited by the power in the beam, but rather by the I^2R losses in the cavities, particularly at the output. This is a very important point in what follows.

The period between the middle 1940's and the early 1960's was the golden age of microwave tubes. With Fred Terman as Dean of its School of Engineering, Stanford was on its way to becoming the electronics center of excellence in the US, and the Western World. Kompfner's 1945 invention of the helix traveling-wave tube in England opened the way to broadband amplifiers. Helix TWTs were limited in power, but the invention at Stanford of the "ring-bar" circuit[21] and of the "coupled cavity" TWT[22] made possible high-power, broadband transmitters. Stanford was at the center of the action. Other Universities also joined the hot new field. Between 1945 and 1965, hundreds of Ph.D. dissertations were written at Stanford, Berkeley and MIT dealing with microwave tubes, accelerators and related devices.

The 1939 Varian paper taught experimenters the world over how to build a basic klystron. The Mark III klystron development 10 years later provided the detailed technology to put at least five companies in the business of making high-power klystrons. Large radars, employing "super-power" klystrons reached their peak in the Cold War era. They were deployed in huge phased arrays in Alaska, Canada and Greenland to detect Soviet missiles, in the event of an attack over the North Pole (Fig. 10). Later, even more powerful klystrons were used on Kwajalein Island to track ballistic missiles launched from California and the anti-ballistic missiles fired to intercept them. Similar klystrons powered the Missile Site Radar systems protecting missile silos in the continental US.

Radar was a practical by-product of Britain's initial attempt to develop a directed energy weapon for air defense. As early as 1934, the British Air Ministry offered 1000 pounds to anybody who would demonstrate the apparatus necessary to kill a sheep at a range of 100 yards.[23] One of the scientists who studied the problem was Robert Watson-Watt. He concluded that a death ray was not practical but in the process invented modern radar. However, the death ray idea did not die. It was revisited in the 1960's. A major U.S. Army program designated as Project 140, and

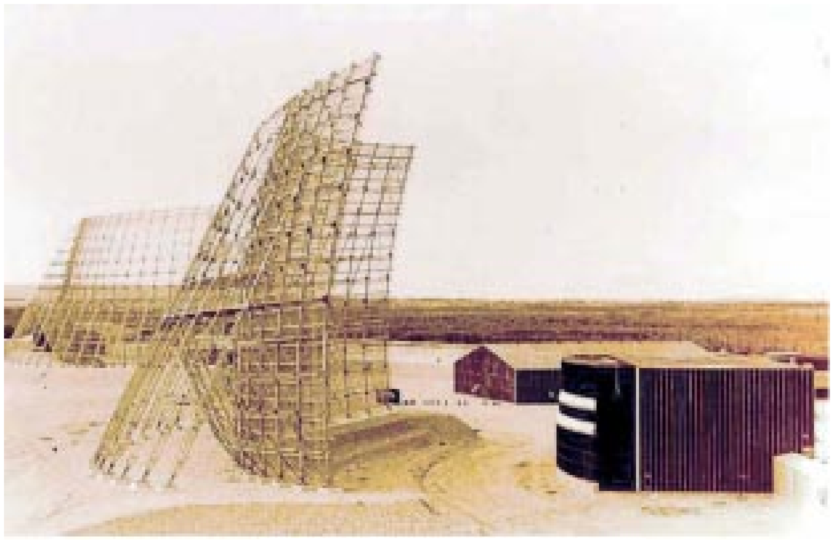


Fig. 10 BMEWS Site

classified SECRET, was awarded to General Electric, to develop an electron device capable of 1-MW CW power at X-band. The objective was to use it against ground troops in the battlefield. The death-ray secret weapon was apparently never produced, and no sheep died. However, some pioneering research was done. Multi-beam klystrons (MBKs) and the original version of the FEL, the Ubitron,[24] were first conceived in the US under Project 140. The MBK was not pursued further in the US, but it was adopted and developed in the USSR.

Project 140 resulted in some new ideas, but no usable hardware. There was, however, an Air Force follow-on program in the 1960's with the same goal, 1-MW CW at X-band, but without any death ray implications. This work was carried out at Eitel-McCullough Inc. As indicated earlier, the power-limiting mechanism in a well-designed klystron is not the average power in the beam, but rather the power that must be dissipated as losses in the output circuit. (In the case of very high-peak power pulsed klystrons, surface gradients at the output circuit may limit power, rather than surface losses.) The design of the 1-MW X-band klystron was an interesting compromise between choosing a low perveance for better beam optics and low interception on one hand, and a lower beam impedance for tighter output coupling, lower Q_e, and better circuit efficiency, on the other. The Air Force contract produced the desired 1-MW klystron, named the X-3030 (Fig. 11).[25] The principal problem in designing the device was to develop an extended interaction output cavity that could be adequately cooled. As this figure shows, the collector in the tube dwarfed the rf cavities. Since the surface available for cooling the output cavity is proportional to the wavelength, it is evident that the maximum average power obtainable from a klystron scales as the square of the wavelength. Thus, since the X-3030 produced 1 MW at 8 GHz, a klystron at 80 GHz could produce 10 kW, if properly designed and cooled. As it happens, microwave amplifiers at 80-90 GHz have apparently only produced approximately 500 watts, to date.

Fig. 11 X-3030 1 MW CW X-Band Klystron

Meanwhile, behind the Iron Curtain, klystron development, after World War II, became increasingly secretive. Some original Russian designs were conceived at the Leningrad Institute where the Heils did their research. (The Russians consider the Heils as the inventors of the klystron.) As early as 1940, Kovalenko, working in Leningrad, proposed a strip-beam klystron,[26] which is the ancestor of modern Russian high-current MBKs (Fig. 12). A strip beam can support

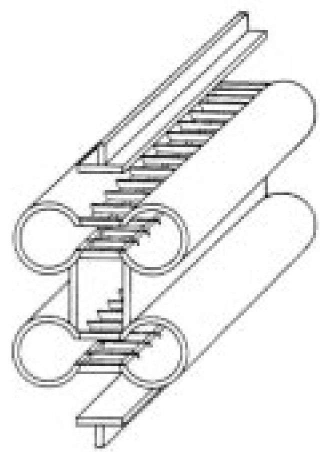


Fig. 12 Kovalenko's Sheet-Beam Klystron

a higher current, without compromising beam optics, if the "perveance per square" remains modest. At ISTOK, a vacuum tube facility near Moscow, Russian engineers and physicists developed a large family of MBK's for radar and communications (Fig 13). There are substantial advantages to the MBK, once certain associated electron optics problems are solved. They have lower beam voltage, wider bandwidth and higher efficiency than single beam klystrons of comparable power and gain. The Russians developed the necessary optics and MBKs have been in production at ISTOK and several other factories for several decades. The wraps are now being removed from this technology and interesting new possibilities are opening for multiple-beam klystrons. The lesson we are learning from the Russians is to use more than one beam if more power is needed than a single beam can provide, or if a lower voltage or a wider bandwidth is desired.

The Reagan Star Wars era in the 1980's and suspicions of Russian directed energy work rekindled the idea in the US of beaming intense microwave energy at targets. This time these targets were much more substantial than sheep or other domestic animals. It would appear that, initially at least, there were aspirations of

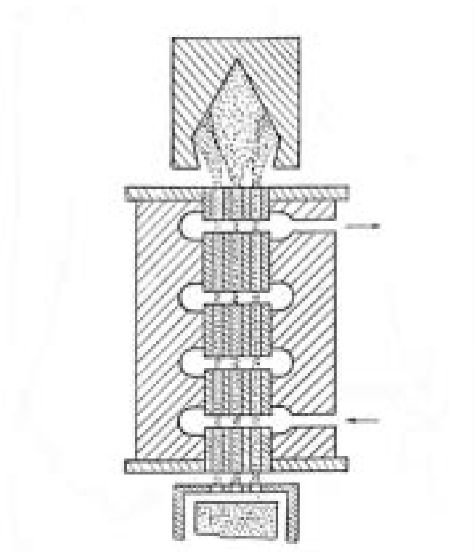


Fig. 13 Sketch of Russian Multiple Beam Klystron

disabling incoming ballistic missiles, by heating up the nose cones with microwave energy. By applying elementary principles, this proved to be a rather tall order; just as killing sheep was 50 years earlier in Britain. However, a related idea showed promise. The radar and communication receivers of the 1980's were not as hardy as those of the war years, which relied on vacuum tubes in their preamplifiers. Today's "front ends" employ delicate transistors, which can be burned out if they are exposed to microwave radiation of sufficient energy. Thus, was found a new direction for directed energy. The Star Wars effort engendered a community of plasma physicists who were recruited to create huge neutral beam and laser weapons for missile defense. With the Cold War won and Star Wars in severe recession, some were attracted to microwave directed energy. They brought with them the technology of producing beams of thousands of amperes and accelerating them to hundreds of kilovolts. This amounted to many gigawatts of beam power and an opportunity to convert it to at least a few gigawatts of microwave power, if suitable modulation and energy extraction schemes could be found. The military believed that one or more kilojoules of energy at a relatively low frequency would do the necessary damage to hostile electronics. All this produced a new field of endeavor, named by the plasma physicists HPM, as indicated earlier. Devices such as "Relativistic Klystron Oscillators," or RKOs, and "Magnetically Insulated Oscillators," or MILOs,[27] were developed and the military were intrigued. HPM was generously funded, but there remain a number of fundamental problems, with no solutions to date.

The advances in the klystron state-of-the-art inspired by the cold war were augmented in the 1960's by an AEC contract at Stanford to develop a two-mile linear electron accelerator. The machine required 250 klystrons, each producing 25 MW at S-band, with three-microsecond pulses. At the time, this was not only the largest single system using klystrons ever contemplated, but a major technical challenge in klystron technology, because these klystrons were required to operate in large permanent magnets. Four different tube companies produced prototypes and the accelerator was commissioned in 1966. Klystron development activities at SLAC continued gaining momentum through the 1980's, when a conversion of the 2-mile accelerator into an electron-positron collider required still more powerful klystrons. The tube developed for the Stanford Linear Collider (SLC) was a 65-MW S-band klystron,[28] which almost tripled the state-of-the-art in power for pulsed klystrons.

IV. CURRENT TECHNOLOGY

The linear collider concept, first demonstrated at Stanford, provided an alternative to e^+e^- storage ring machines, which, because of synchrotron radiation losses, have reached their limit with CERN's LEP.[29] However, since linear colliders do not recycle their beams, they are voracious consumers of microwave power, which for a fixed length machine, must increase as the square of the collision energy. The Next Linear Collider (NLC), now under development at SLAC, with a goal of 1.5 TeV, will require more than 8,000 X-band klystrons along a 20-mile length (Fig. 14). The NLC is likely to be an international collaboration, which may secure it a better fate than the SSC in Texas.

The Stanford design for the X-band machine calls for 75-MW, 11.4 GHz klystrons. Klystrons at this power and frequency did not exist anywhere in the world. They have been under development at SLAC during the last 8 years. In addition to the unusually high-peak power, the design of these tubes is complicated by the fact that the power budget for the collider simply cannot accommodate 10 kW, or more, of solenoid power to focus the beam of each klystron. A beam-focusing system of periodic permanent magnets (PPM) commonly used in lower-power TWTs, but never before used with high-power klystrons, had to be designed. An early prototype was successfully tested recently[30] (Fig. 15). Test results are compared in Fig 16 with a simulation, which takes into account the PPM beam focussing (See Klystron Tutorial). In parallel with prototype development, SLAC is also engaged in a Design for Manufacture program aimed at a drastic cost reduction of this klystron. If, as planned, a multinational collaboration of physicists builds the machine early in the next century, and if the SLAC X-band design is adopted, manufacturing drawings will be made available to industry for producing the tubes. Were this happening today, the annual sales volume of klystrons for the NLC would match the total sales of all US klystron manufacturers.

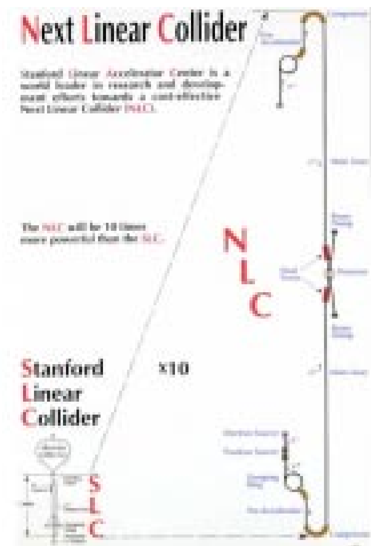


Fig. 14 The Next Linear Collider Compared to the Stanford Linear Collider

V. THE FUTURE

After X-band colliders reach 1 TeV, millimeter-wavelength colliders will be needed to attain 5 TeV or more, and presumably initiate completely new physics. At

SLAC, such colliders are being considered. As usual, new high-power sources are needed and, once more, the klystron is a candidate. A fresh approach is in order,

Fig. 15 50-MW PPM X-Band Klystron

however, because the methods used to date in making klystrons are simply not realizable at 3 millimeters. A combination of Russian, US and German technologies

50 MW X-BAND PPM KLYSTRON SIMULATION AND TEST RESULTS

Item	Experiment	Simulation	Unit
Peak RF Power Output	56	59	MW
Peak Beam Power	93	91	MW
RF Efficiency	60	65	%
Gun Perveance	0.66	0.60	μK
Beam Voltage	459	465	kV
Beam Current	205	190	A
Intercepted Beam Power @ Rated RF Output	1	0.0	%

Fig. 16 50-MW Klystron Data

has been employed to arrive at the practical design. The Russian idea is the use of multiple beams. This is effective at the lower frequencies, but at 3 millimeters (W-band) it is necessary to augment it with PPM focussing, a technique which has worked very well for SLAC at X-band.

There remains the problem of fabricating W-band klystron cavities. Clearly, conventional machining is inadequate. A new process, borrowed from the semiconductor industry is the solution. This is LIGA,[31] a combination of deep-etch lithography and electroforming, developed in Germany several years ago. It requires synchrotron radiation to expose photo-resist that can be as thick as one millimeter or more. After development and electroplating, it is possible to create W-band cavity features, with 2-3 micron tolerances and excellent surface finishes (Fig. 17).

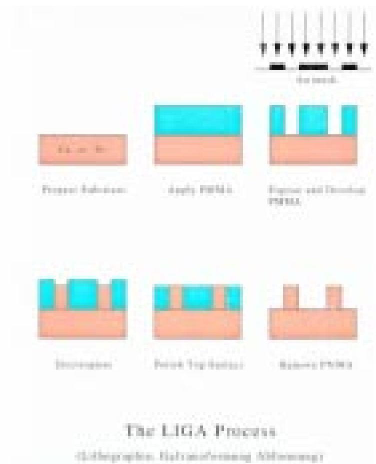


Fig. 17 LIGA Process

The result of applying these ideas to the design of a high-average power W-band amplifier is shown in (Fig. 18). This is a module composed of six "klystrinos," each producing 125 kW, and operated in parallel. They have separate electron guns, cavities and PPM stacks, but a common vacuum and a common beam dump. The individual beam perveance is 0.06×10^{-6}, which is uncommonly low, but necessary for the periodic focussing and the packaging that PPM makes possible. The required voltage of 125 kV is not excessively high for a combined output power of 750 kW.

An average power well in excess of 3 kW should be possible with conventional cooling and power densities up to 500 watts/cm^2. If more advanced micro-channel

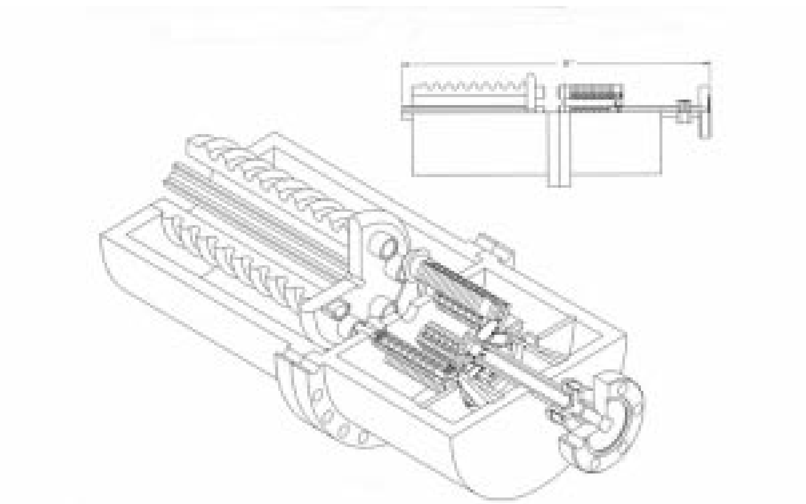


Fig. 18 W-Band Modular Klystron

cooling methods are used, an average power of 10 kW or more might be attained. Output power is extracted through a ceramic window in a cylindrical waveguide fed symmetrically with TE_{10} rectangular waveguides from the outputs of each klystrino, which launch a TE_{01} mode in the common output waveguide. The entire device is less than 10 inches long, with a 6-inch diameter. These dimensions should make possible "stacking" several such units and combining their outputs for even greater peak and average power.

Realizing the basic device is based on two basic assumptions and several design features. The assumptions are:

1. The output cavity can be fabricated with an unloaded Q of at least 1000. This is theoretically possible, but is as yet unverified.
2. The electron gun and the "klystrino" bodies can be aligned well enough for a 0.5 mm beam to traverse a 6 cm-long, 0.8 mm diameter drift tunnel, with little or no current interception.

A basic design feature is to use a very low perveance for each "klystrino." There are two reasons: The lower perveance makes periodic focusing possible, as the NLC X-band klystron has demonstrated. A high conversion efficiency also results. The downside is a high Q_e and hence a low circuit efficiency. This is the reason for the high-Q_0 requirement. Another novel feature is that the "klystrinos" operate in a common vacuum, with their guns and common collectors open (these are two principal sources of gas in a klystron) so that they can be pumped efficiently. The open construction allows precise alignment of guns and "klystrinos" prior to final assembly.

The second major design feature is the method used to correctly phase the six individual klystrino outputs, so that a pure TE $_{01}$ mode can be launched in the circular waveguide (Fig. 19). This is done by initially dividing the input to the device into six separate rectangular waveguides in a manner reverse to that used at the output. In series with each one is a PIN diode network capable of changing the

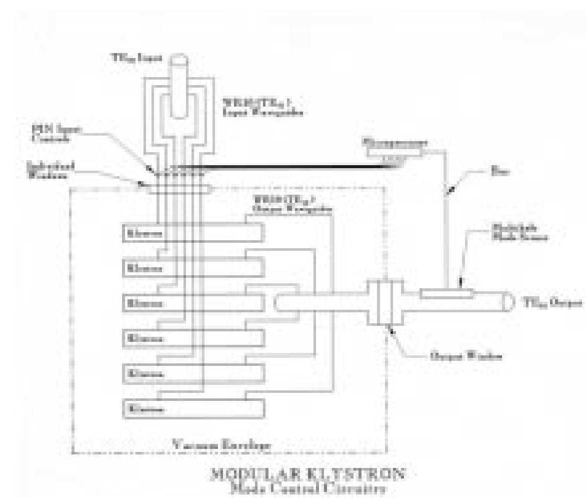


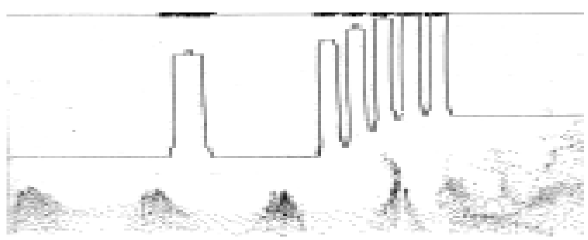
Fig. 19 Modular Klystron Controls

amplitude and phase of the power in each waveguide. The six input waveguides then penetrate the vacuum through ceramic windows and feed the six klystrinos. At the common output of the device, specially designed directional couplers sense the mode configuration in the circular waveguide. Signals from these devices feed a microprocessor, which determines the correct phasing of the six inputs and provides appropriate signals to the PIN networks. The technique is based on a very similar arrangement used in pulse compressors for the NLC, which employ several independently controlled modes in circular waveguide. This “smart tube” method can have important applications in the design of other high-power klystrons.

The modular klystron is an important development. Commercially available W-band sources in this country are coupled-cavity TWTs, producing up to 500 W of average power and requiring heavy solenoids to develop the fields necessary for focusing the electron beam. These tubes are very bulky, expensive, and not very efficient, especially if the solenoid power is taken into account. Russian gyro-klystron amplifiers also produce comparable power. These require even higher magnetic fields, utilize superconducting solenoids and are also rather inefficient. The proposed modular klystron design should have an overall efficiency of approximately 35 %, the product of 50% conversion efficiency and 70% circuit efficiency. Gain should be 40 to 50 dB. The modular klystron has potential military applications that will probably not emerge until the device is demonstrated. We expect to build a single klystrino prototype within the next year. There can be little doubt that the entire modular device is realizable once the design of a single klystron is demonstrated.

One thing is certain: accelerator physicists will design machines to take advantage of these new sources. At SLAC, such a project, aiming at 3-5 TeV, 91 GHz collider, has been under way for a year. It is obvious then, that the first use of the modular klystron source will be to power a test accelerator. That is how high-power klystrons started at Stanford 60 years ago, and it is entirely fitting that a new advance in klystron technology will take place for the same purpose, and at the same place.

A KLYSTRON TUTORIAL



A “CONDOR” simulation One- half of a figure of revolution is shown radially exaggerated for better bunch definition.

The rf current produced by the bunched beam, moving from left to right, causes the output cavity (the “extended interaction” circuit to the right of the illustration above) to “ring” at its fundamental frequency. The current induced at the output circuit produces a voltage across it, which slows the beam down, converting its kinetic energy to rf energy in the cavity, and dispersing the bunches. Power is taken out by a waveguide (not shown).

The electrons shown between bunches detract from good efficiency. More electrons can be directed toward the bunches by inductively tuned cavities placed before the output circuit (as the single TM_{01} resonator shown above), or by one or more 2nd harmonic cavities upstream.

Space charge forces prevent tighter bunches from being formed. These forces increase with beam perveance, which is defined as:

$$K = \frac{I_0}{V_0^{3/2}}$$

Hence, the lower the perveance, the tighter the bunching and the conversion efficiency.

A gap resistance R_g must be chosen to optimize the gap voltage for good conversion efficiency. Its value depends on the coupling coefficient M between beam and circuit, and on the ratio of rf to dc current, I_1/I_0. M and I_1/I_o are usually determined by simulation. An empirical formula for the gap resistance R_g is:

$$R_g = \frac{V_0}{I_0} \frac{1}{M^2 \frac{I_1}{I_0}}$$

The required gap resistance and the cavity R/Q determine how tightly the output cavity is to be coupled to the output waveguide (or how low the Q_e can be). R/Q is proportional to the ratio of the square of the gap voltage to the energy stored in the cavity.

$$Q_e = \frac{R_g}{\frac{R}{Q}}$$

A low Q_e implies better circuit efficiency and wider bandwidth for the klystron. Good design calls for a high coupling coefficient and R/Q, either of which results in a low Q_e.

Low-perveance klystrons have good efficiency, but because of a higher R_g, have narrower bandwidth and lower output circuit efficiency.

$$\eta_c = \frac{Q_0}{Q_0 + Q_e}$$

In pulsed, high-peak power klystrons, it is essential to minimize the surface gradients at the output circuit to avoid rf breakdown. A single cavity is often unsuitable and "extended" circuits must be employed. Their function is to develop the required interaction voltage over a longer distance to reduce surface gradients.

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