RECENT DEVELOPMENTS WITH KLYSTRONS AND MODULATORS

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ABSTRACT

The design goals for new Klystrons are governed by the rf power needs and efficiency requirements of the various linear collider proposals which are presently being evaluated. We review the existing tubes and modulators for each collider project and discuss some of their specific problems and (planned) solutions. Due to the 1.3 ms long pulses required for TESLA the stored energy in the modulator and the size of the pulse transformer are significantly larger than for any other project. The X-band proposals are the other extreme. Here the short Klystron pulse length which is of the order of a µs calls for modulator pulses of 6-700 kV and a rise time of a few 100 ns. Hence a completely diffrent modulator design is necessary

Future tubes for linear collider upgrades which are in the development stage are also discussed.

1 INTRODUCTION

In modern high energy accelerators Klystrons play an essential role in the generation of rf power in the frequency range from a few hundred MHz to about 15 GHz. At the lower frequencies cw power levels of the order of 1 MW have been routinely produced whereas the power attainable in short pulses exceeds the 100 MW level.

The basic mechanism of generating rf power in a Klystron consists of subjecting the dc electron beam emerging from a cathode to the rf field of an input cavity which is driven by an external low power rf generator. The resulting velocity modulation of the beam transforms into an intensity modulation by passing the beam through a drift tube. The output cavity which is located at the end of the drift space is excited by the rf component of the bunched beam. Rf power can be extracted by a coupling loop or slot. The remaining low energy in the electron beam is then dissipated in the collector.

In practice there are several intermediate cavites to enhance the bunching efficiency and hence the dc to rf conversion efficiency of the Klystron. The art of the designer lies in the optimization of the dc and rf high voltage gradients occuring in the gun and in the cavities, of the number of cavities and their tuning, of the length of the drift tubes and of the beam focusing.

The main limitation for high peak power and pulse duration in Klystrons is electrical breakdown which can occur along the insulators or between the electrodes of the gun and in the rf circuits of the tube. For very high peak power arcing can occur across the gap of the output cavity since the gap voltage has to be comparable to the gun voltage for high efficiency. The output window is also a very critical element.

Due to the space charge forces of the beam which counteract the beam bunching the electronic efficiency of a Klystron is highest for minimum beam current I and maximum beam voltage U. The latter is limited by the maximum possible electrical field strength in the gun and by the pulse length. A characteristic quantity which allows to estimate the maximum achieveable efficiency of a Klystron is the perveance defined as $P=I/U^{3/2}$. For $P=2*10^{-6}$ an efficiency >45% is possible whereas at $P=0.5*10^{-6}$ one may hope for more than 70% efficiency.

A fact which is often ignored is that reducing the rf output power by decreasing the drive power alone will also decrease the efficiency since reducing or switching off the rf drive power has no influence on the average dc electron beam current, and in the latter case the full energy of the beam is wasted in the collector. The efficiency of the device becomes zero.

Large power variations are performed more efficiently either by variation of the operating voltage or by means of a modulating anode or a gridded gun.

For high power tubes which operate at cathode voltages well above 100 kV there are practically no tubes with a modulating anode because of isolation problems, and the technology of gridded guns for high power tubes is not yet very mature. Therefore most high power Klystrons need a pulsed high voltage power supply called modulator. The modulator usually is a very sophisticated device since it has to deliver pulses which are typically in excess of 100 kV at current levels well above 100 A. The wall plug to rf power conversion efficiency depends critically on the rise and fall time of the modulator pulse since rf power can essentially be generated only in the flat top portion of the pulse. In view of the estimated 100-200 MW rf power consumption of the various linear collider projects which are currently being discussed each per cent of efficiency loss means additional 1-2 MW extra power.

In the following we will focus on recent developments of pulsed Klystrons which are needed for future linear colliders. The state of the art of cw Klystrons is represented by the 352 MHz tubes which deliver up to 1.3 MW cw rf power for LEP. These Klystrons are offered by several manufacturers. Similarly there are 500 MHz Klystrons running at DESY which deliver cw power levels in the 800 kW range, and there are 1.2 MW Klystrons running at KEK at 508.6 MHz. The efficiencies of all these tubes are in the 65 % range. Remarkable are also two devices presently under development in Japan; an 1.2 MW cw L-band tube with 53 % efficiency and an 800 kW tube for 5 GHz and 69 % efficiency.

2 L-BAND KLYSTRONS

The 1.3 GHz operating frequency of TESLA represents the lower end of the frequency spectrum spanned up by the linear collider proposals. On the other hand the rf pulse length of 1.3 ms is by far the longest. For the TESLA TEST FACILITY (TTF) two TH 2104 Diode-Klystrons were bought from Thomson which can deliver up to 5 MW rf pulses of 2 ms length at the rep. rate 10 Hz. The efficiency is 45 %. These tubes which run at 130 kV gun voltage represent today's state of the art for so long pulses.

From existing tube performances the empirical relation $E*V=100/\tau^{.34}$ between achieved pulse length τ [s], max. field strength E [kV/mm] in the gun region and gun voltage V [kV] has been established [1].

Because of the long pulse length the modulator was a challenge too. It was specified for 130 kV, 95 A pulses of 2.2 ms length. There is a lot of experience with pulse transformers for pulse-lengths in the range of some μs, but much less in the ms range. Due to the long pulse length the energy to be delivered by the modulator per pulse is of the order of 25 kJ as compared to less than a kJ in most other cases. We investigated the possibility to use a PFN in conjunction with a pulse transformer. Technically this would have been possible, but the preferred alternative solution of an 1.4 mF capacitor charged to 9.6 kV as an energy storage element in conjunction with a bouncer circuit and a pulse transformer seemed less expensive and was built at FNAL. The prototype of a 2 ms pulse transformer was delivered by industry in August 1993.

The pulse rise time is less than 100 μs, and the voltage droop during the pulse is 1%. The overall wall plug power to useful HV conversion efficiency is 86%. "Useful" means that only the flat top of the HV pulse which is good for rf generation has been taken into account.

Installation at DESY and successful final commissioning took place in April 1994. Since then the modulator has been regularly used without any problem. Two more such modulators are presently being built at FNAL [2].

DESY has decided to procure also a prototype of a **S**uperconducting **M**agnetic **E**nergy **S**torage (SMES) Modulator. Here the HV pulse will be generated by an IGBT switch which commutes the current flowing in a SC coil into the pulse transformer primary during the pulse. Recently, in a successful proof-of-principle experiment, 3 kV pulses were generated with a SMES current of 440 A [3]. Switching was done by a prototype IGBT switch.

A contract with industry has been signed for the development of a 1.3 GHz 10 MW multibeam Klystron with 1.7 ms pulse length and 10 Hz repetition rate. Since the specified efficiency is between 70% and 75% the microperveance must be about 0.5 which, for a single beam 10 MW Klystron, implies a gun voltage of 240 kV. The design of a gun at this voltage level and pulse length would be very critical. Therefore the solution of a multibeam Klystron with 7 beams, each having the microperveance 0.5, has been favoured. The gun voltage will be 110 kV and the total beam current 130 A. There will be two rf output windows. The solenoid focusing power will be only 4 kW.

A prototype of a 64 kW 4 beam Klystron operating at 425 MHz has demonstrated an efficiency of 44 %. The cathode voltage was only 18 kV [4].

A proof of existence and feasibility of 5 MW L-band MBKs operating at ms pulse lengths comes from the Moscow Meson Factory, where 33 MBKs are running. These tubes have 6 beams and the operating voltage is only 75 kV. The microperveance of 1.4 per beam should allow for a higher efficiency than the 40 % of the actual tubes.

I would like to mention two other L-band projects: The "Intense Beam Klystron" known as the Annular Beam Amplifier (ABA) plans to provide single shots of 2 GigaWatt pulses resulting from a 400 kV, 16 kA beam [5]. The other is a One-Microsecond, L-Band Relativistic Klystron Amplifier with a 600 kV, 5 kA beam designed for 1 GigaWatt pulses. Peak power pulses approaching 0.5 GigaWatt and 0.5 μs half power width have been obtained [6].

3 NEW RESULTS ON S-BAND SOURCES

The main recent achievement in the S-band domain is the 150 MW Klystron which was designed and manufactured at SLAC for the DESY-Darmstadt S-band Linear Collider project.This rf output power is a 150 % increase over the S-band tubes currently used in the SLAC linear accelerator. Some important design parameters of this tube are summarized below:

Frequency	3 GHz	RF output power	150 MW
Beam voltage	535 kV	Beam current	700 A
RF pulsewidth	3 μs	Efficiency	> 42%

For some combinations of solenoid curent and gun voltage an rf oscillation appeared at the frequencies 8.5 GHz and its harmonic at 17.18 GHz. A possible explanation is that a slightly off-axis beam is further deflected by an asymmetric mode in a cavity and after spinning around in the focusing field reaches another cavity which can be excited at approximately the same frequency. An oscillation can build up by feedback through the drift tube. However, the region of stable operation is sufficiently large [7].

The first 150 MW tube was delivered to DESY in April 1994, the second in July 1995.

In the second Klystron the oscillations were successfully eliminated by replacing the copper drift tubes by lossier stainless steel tubes.

The single cell output cavity of the first tube was replaced by a double cell standing wave cavity. The efficiency of the second tube is 45%. There are four output windows on each tube.

The modulator which is used at DESY to run these Klystrons is a copy of the line type pulser which was designed and built at SLAC [8].

The pulse forming network consists of four parallel lines with ten sections each. They are charged up to the maximum voltage of 50 kV. Because of the high current of up to 17.7 kA two thyratrons are used in parallel connected to two PFN lines each. Special attention has been given to minimize wiring inductances which are, together with the leakage inductance of the 1:23 pulse transformer, the limiting factors for the measured output voltage rise time of 600 ns.

Very recently the development of a 150 MW S-band tube was also reported by Thomson. Here the pulse length was limited to about 1 μs by the modulator capacity [16].

4 DEVELOPMENTS OF X-BAND KLYSTRONS

There are three X-band Linear Collider proposals which involve the development of new Klystrons, namely NLC (SLAC) and JLC (KEK) and VLEPP (Novosibirsk, Protvino).

At SLAC 8 prototype Klystrons, known as the XC series, have been evaluated with the goal of producing 100 MW rf output power at X-band. The lessons learnt from these studies were that single gap output cavities and pillbox rf windows could not work at the required power levels. The best result achieved with the latter was 25 MW at 1 μs pulse width.

For the subsequent XL Klystron series the effort has shifted to the development of a reliable 50 MW source with the eventual upgrade to 100 MW. The main parameters of the XL-1 tube are:

Frequency	11.424 GHz	Peak output power	50 MW
Beam Voltage	440 kV(465 kV)	Beamcurrent	350A(190 A)
Microperveance	1.2 (0.6)	Efficiency	≤40%(57 %)

The values in parantheses are simulation results for a PPM-focused tube.

The output circuit of the XL-1 is a three-cell, standing wave, disk- loaded wave guide. The traveling wave output window operates in the circular TE_{01} mode which has no electric field at the critical region of the ceramic to metal brazing joint. In a resonant ring this window has demonstrated the capability of transmitting 100 MW of rf power at pulses of 1.5 μs width.

Now four 50 MW XL Klystrons are in operation and ready for use in the NLC.

A PPM-focused tube, in which a periodic array of permanent magnets replaces the solenoid, is in the final stages of computer simulation and mechanical design.

The output circuit of the XL-4 is a 4-cell traveling wave structure tapered in impedance and velocity. The velocity taper ensures that the wave remains in synchronism with the slowing beam for maximum energy extraction. The impedance taper, which is achieved by an increasing inner diameter for each successive cavity disc, ensures nearly constant rf voltage per gap. In addition, it accomodates the beam expansion [9].

Due to the short pulses and the high voltage required for these X-band Klystrons it becomes particularly important to minimize the modulator HV pulse rise time. The limiting factors - transformer leakage inductance, internal inductances of lumped capacitors and wiring inductances - can be minimized by reducing the transformer step-up ratio and eliminating lumped capacitors. In the symmetric Bluemlein PFN configuration the pulse transformer primary sees the total PFN voltage rather than only half of it as for an ordinary PFN. Hence the transformer step-up ratio can be halved. To avoid lumped elements the use of lengths of smooth transmission line (PFL) has been proposed. The main design (max) parameters of the NLC modulator are listed below:

Output pulse voltage	517 kV	Output pulse current	557 A
PFL voltage	75 kV	Pulse energy width	1.55 μs
Pulse rise time	320 ns	Net Modulator efficiency	72%

The **T**wo **B**eam **N**ext **L**inear **C**ollider (TBNLC), which is a relativistic Klystron two beam accelerator, has been proposed as an alternative rf power source for the main linac of the NLC. In a recent successful reacceleration experiment a 5 MeV, 1 kA beam from an induction linac was modulated by a transverse deflection technique to generate several hundred amperes of rf current at 11.4 GHz.

The rf power was extracted in three traveling wave output structures. Two induction modules, each pulsed at 250 kV, were located between the output modules for reacceleration. Total output power pulses of up to 172 MW have been achieved with a phase stability in the range ± 3^0 .The measured conversion efficiency from beam to rf power was 7 %. The estimated electronic Klystron design efficiency is close to 90% and the estimated overall mains power to RF efficiency 35-40% mainly limited by the core losses of the induction cells [10].

Based on the experience gained in this experiment it is intended to build a prototype relativistic Klystron with an extraction section of 8 m length for detailed study of beam dynamics.

At KEK the X-band R&D has been carried out since 1988. The most advanced tube from this project is the XB-72k which has the following design values:

Peak output power	120 MW	Cathode voltage	550 kV
Beam Current	490 A	Microperveance	1
Gain	53 dB	Efficiency	47%

Up to 95 MW output power were obtained for pulses of 70 ns length. The demonstrated efficiency was 36% at 50 MW.

An autopsy of the first XB-72k showed that the beam transport was excellent since there was no evidence for beam interception throughout the drift section and the output cavity. The output gap showed serious damage caused by rf discharges, and a new multi-gap design is in progress [11]. Similar experiences were made at SLAC.

The Klystron pulse length and the usable portion of the modulator pulse are only 400-800 ns. Therefore, here as well as at SLAC, the Bluemlein type configuration of two identical PFNs which can double the output voltage compared to the ordinary PFN is the modulator foreseen for this tube.

The projected and achieved Bluemlein modulator parameters are summarized below:

	Design	Achieved
9-stage PFN voltage	120 kV	86 kV
Step-up ratio	1:5	1:7
Rise time	150 ns	250 ns
Flat top	500 ns	600 ns

The rf source for the VLEPP facility is an amplifying relativistic Klystron with the following parameters:

Operating frequency	14 GHz	Peak output power	150 MW
Pulse duration	0.5 µs	Beam voltage	1MV
Beam current	300 A	Saturation gain	80 dB
Cathode loading	4 A/cm^2	Efficiency	50 %

A unique feature of this Klystron is its gridded gun and the associated modulator scheme. The honeycomb oxide cathode consists of 37 separate microcathode cells with the sphere radius of 25 mm. The grid electrode has holes which are congruent with the cathodes. Therefore each cell operates as a separate gun with Pierce optics. After passing the grid all beams form the macrobeam which is accelerated.

Due to the grid the VLEPP Klystron can be supplied by a constant voltage source. To reduce cost one common source for 20 Klystrons is foreseen. For pulsing the cathode there is a coaxial **P**ulse **F**orming **L**ine (PFL) of 0.5 µs electrical length for each Klystron. In order to increase the maximum tolerable electrical field strength the line is pressurized up to 12 atm with SF_6. A 5 m piece of the PFL line has been tested up to 960 kV.

Focusing will be achieved by permanent Nd-Fe-B magnets. The maximum field strength is 4 kG. There are one input- and 7 gain cavities. The output stage is a 14 cell traveling wave cavity with the maximum field strength 700 kV/cm and two symmetrical wave guide power outputs each with a pill-box window of 3λ diameter.

So far pulses of 50 MW output power and of 0.7 µs length have been obtained at 1 Hz rep. rate. The gain was over 90 dB. At larger power levels self exitation occurred in the Klystron which could be damped by inserting absorbing materials into the drift tubes. Then output power pulses of 45 MW at 250 ns and about 30 % efficiency were achieved. In a shorter pulse 70 MW were obtained [12].

The pulse compression sheme foreseen for VLEPP involves a **B**arrel shaped **O**pen **C**avity (BOC) in which essentially the TM_{31-1-1} "whispering gallery mode" is present. The unloaded Q is about 200000. High power results obtained at KEK are listed below.

Compression ratio and efficiency	4.55 and 72%
Input/output pulse length	500/110 ns
Power gain and transmission efficiency	3.3 and 95%
Maximum power in P.C. system	150 MW

The last number was limited by the available Klystron power. The design value is 250 MW.

I would like to mention a few more X-band rf sources which seem promising, but are still in an early stage of development.

The Magnicon is a source developed at Budker Institute (Novosibirsk). It consists of a continuous electron beam which is deflected by the rf magnetic field of a circular deflection cavity [13].

In the subsequent drift space electrons deviate from the device axis and get into a stationary magnetic field of a solenoid. While entering the magnetic field the longitudinal velocity of the electrons is transformed into a rotational transverse one.

Further on, traveling along a helical trajectory in the output cavity, the electrons excite a TM_{110} oscillation mode. If the cyclotron frequency is equal to the one of operation, then the interaction can remain effective during many periods of rf oscillation resulting in a very high efficiency.

Feasibility of the magnicon has been demonstrated by two prototypes. One has delivered 2.6 MW rf pulses of 30 µs length at 915 MHz. Here the electronic design efficiency was 85%. The efficiency actually reached was 73% due to the quality of the aluminum alloy used for cavity fabrication. The other magnicon was a frequency doubler which has demonstrated 25 MW output power at 7 GHz for 2 µs pulses. In this case the design efficiency of 60 % was reached.

A recent experiment with a frequency doubler magnicon yielded 20 MW pulses at 6.998 GHz for 1.3 µs pulse length. The device was operated at 400 kV beam voltage and 200 A current. Limitations on the output power and the measured efficiency of only 25% were caused by non-linear excitation of parasitic modes in the penultimate cavities. An improved design has recently reached 30 MW pulses at 35 % efficiency and the designers are optimistic to overcome the 50 % margin soon.

There is also work going on at NRL to build an 11.4 GHz magnicon with the beam parameters 500 kV and 200 A. The prototype has not yet given high power output.

It has been claimed that an L-band 10 MW magnicon for TESLA could be built with an efficiency in excess of 78 %.

A possible future x-band source may result from the BNL-MIT-SLAC Cluster Klystron project [14] which is a Multi-Beam-Klystron. In its final version the cathodes of this tube will be located in a high pressure tank because of the high DC potential of 360 kV. The beam current for each of the six beams is 100 A. Hence the microperveance is .46 and the expected efficiency is 73% corresponding to the output power 26 MW per beam. The hollow beams are generated in a **M**agnetron **I**njection **G**un (MIG) with its primary anode serving as a modulation anode, thus avoiding a modulator.

Since the high pressure tank is not yet available presently tests of the performance of the MIG-gun, of the beam shape and stability on axis, are made at 100 kV. It is planned to simulate the off axis operation by modifying the focusing magnetic field. Then a diagnostic 4 cavity Klystron will be mounted to check the rf performance. The foreseen rf pulse length is 1 µs.

Initial performance of a "High Gain, High Efficiency 17 GHz Traveling Wave Relativistic Klystron" was recently reported [15]. This prototype tube was designed with an array of 16 cavities distributed over a distance of 42 cm. The traveling wave output structure is equipped with higher order mode (HOM) suppression circuits because studies of the deflection amplification caused by the excitation of HOMs indicated that otherwise pulse shortening would occur even before the beam flattop was achieved.

First tests using the beam of an MIT electron source were performed at 560 kV gun voltage and 95 A collector current. Rf pulses of 26 MW peak power and 150 ns width were obtained. The saturated gain was 67 dB and the efficiency was 51-52%.

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