KLYSTRON GUN ARCING AND MODULATOR PROTECTION

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Abstract
The demand for 500 kV and 265 amperes peak to power an X-Band klystron brings up protection issues for klystron faults and the energy dumped into the arc from the modulator. This situation is made worse when more than one klystron will be driven from a single modulator, such as the existing schemes for running two and eight klystrons. High power pulsed klystrons have traditionally be powered by line type modulators which match the driving impedance with the load impedance and therefore current limit at twice the operating current. Multiple klystrons have the added problems of a lower modulator source impedance and added stray capacitance, which converts into appreciable energy at high voltages like 500kV. SLAC has measured the energy dumped into klystron arcs in a single and dual klystron configuration at the 400 to 450kV level and found interesting characteristics in the arc formation. The author will present measured data from klystron arcs powered from line-type modulators in several configurations. The questions arise as to how the newly designed solid-state modulators, running multiple tubes, will react to a klystron arc and how much energy will be dumped into the arc.

1. INTRODUCTION

The amount of protection required for a gun arc or a defocused beam in a microwave tube is a continual source of controversy and debate. Historically, tube companies have set protection requirements by their own experience in test. Body current interception was thought to be limited to 10 joules maximum and shutdown within 10 microseconds. In high power klystrons the engineers found out that as the voltage increased, the rate of rise of fault current needed to be limited. 1000A/μsec with a less than10 microsecond maximum shutdown became a typical number used for CW or long pulse tubes with crowbars or series switches. Tube engineers hesitated to put a hard number on the energy that could be dumped into an arc, but 10 joules became a defacto rule of thumb. Thomson in France has listed the highest number I am aware of for allowable arc energy at 40 joules.

High power pulsed klystrons have been classically pulsed using Line-type modulators whose impedance is matched into the klystron by a pulse transformer. In this type modulator the maximum peak current delivered into a gun arc is two times the normal operating current. A klystron was considered to be inherently protected, because of single pulse shutdown and therefore no real attempts were made to measure arc energy levels. SLAC has successfully used this type modulator at high peak power for over 30 years. SLAC continues to require higher peak pulse power and for the NLC (Next Linear Collider) and its Test Accelerator it was decided to operate two klystrons in parallel on the same modulator, which means that the arc current can rise to four times the normal operating current. In fact, the modulator design of choice for the NLC is a solid-state induction modulator, which runs eight klystrons. I decided to try to measure arc energy to see where we are today and feel more comfortable about protecting a klystron. Digital storage oscilloscopes have made this task easier.

2. ARCING IN A VACUUM

To begin to try and understand a vacuum gun arc in a microwave tube one must first consider the fact that the electrode shape, spacing and therefore electric field is chosen to be well below the threshold where an arc would occur. Additionally, the focus electrode (at cathode potential) is intentionally operating at a much lower temperature than the cathode to avoid it becoming an emitter. The most likely cause of the creation of an arc is therefore field emission from the focus electrode. Classically for field emission the potential is raised towards the breakdown threshold of the vacuum gap. At some potential a small electron emission begins (microamperes) after which small changes in voltage will generally produce large changes in emitted current. As the gap is over-voltaged the emitted electrons traverse the gap in less time. Spark gaps, either two pole or triggered, fire in tens of nanoseconds. However, in a microwave tube the cathode voltage remains well below the breakdown threshold and the current builds up slowly (several hundred nanoseconds). This is clearly seen in the experimental data shown below. At the 2000 Modulator Symposium, I reported that Richard Adler of North Star Research "believes, for short pulses the first stage of breakdown is plasma electron emission (private communication). The current increases monotonically until the expanding plasma reaches the anode. The velocity of this expanding plasma tends to be 2-3 cm/microsecond or slower. This is in somewhat agreement with the rise of arc current measured at SLAC[1]. It should be noted that these klystron operate with a vacuum of 10^{-8} or 10^{-9} torr, which enhances voltage hold-off. In another theory field emitted electrons knock off ions on the opposite surface. The ions travel back creating more electrons. The iterative process continues until either breakdown occurs or the voltage goes away.

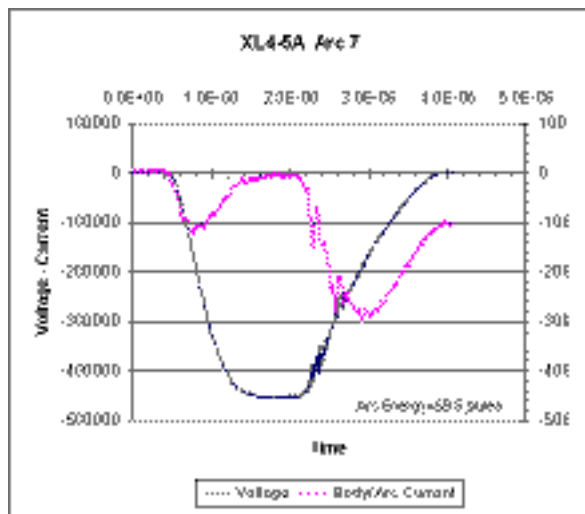## 3. EXPERIMENTAL DATA

3.1 Line-Type Modulator

Development klystrons at SLAC are tested or operated in a number of different modulators with different transformer ratios and impedances. They are Line-type modulators with 25kV charging power supplies, resonant charge and their transformer ratios vary from 15 to 23. Table 1 is a summary of part of the data. Some of this data has been presented previously. The devices tested were S-band and X-band. XL4 klystron arc data was obtained in two different modulators and single and dual tube operation. Examining the data shows that the voltage fall time and the current rise time is much slower than conventional wisdom has believed and takes at least several hundred nanoseconds. During this arc transition, energy is being dissipated and the calculated arc energy is larger than the maximum limits

Table 1
Measured Arc Data - Line-Type Modulators

Klystron	Peak Voltage (kV)	Peak Current (kV)	Energy (joules)	Voltage Fall (ns)	Current Rise (ns)	Pulse PK PWR (MW)
5045 (7)	300.9	550	46.4	3000	400	88.4
5045 (10)	368	525	35.9	1200	200	113
CPI DESY	423	700	47.5	600	300	147
XL4-5A (1)	449.8	600	66.5	1300	800	115
XL4-5A (7)	454	300	59.5	1600	600	76
NLCTA-2 (1739)	443	900	68.5	1000	400	273
NLCTA-2 (1747)	430	900	61	1100	300	269
NLCTA-2 (KL4)	430	1400	60.4	850	1100	120
NLCTA-2 (KL7)	394	1200	23	400	1200	76
XP3-Diode-2	470	477	42	800	600	107
XP3-Diode-3	486	562	41.4	1160	520	116

previously thought allowable. The gap spacing, anode to cathode (focus ring) is large (approx. 2-4cm) as compared with standard spark gap spacing. It takes the arc longer to form and close the gap. It is hard to predict the energy in an arc because it is very dependent upon the arc formation, which is I believe an uncontrolled variable. In the early stages of XL4 development at SLAC, it would take a long time to recover from a gun arc. Discussions about this problem led the klystron engineers to believe that there was poor vacuum at the gun area since the vacuum pump was located a long distance from the gun and there was poor conductance through the X-band circuit. A floating ion pump was mounted at the gun of the XL4. The pump power was supplied from power supply using the klystron heater supply for its input. No other changes were made to the klystron gun and the problem of recovery after a gun arc was gone.

Figure 1 is the voltage waveform taken on an XL4 klystron in the Test Lab on Test Stand 08 and the arc current calculated from the cathode and collector current waveforms. The body current shown at the beginning of the pulse is representative of the capacitive charging current during the rise time of the voltage. This modulator will allow an arc current of approx. 800 amperes. In this case the peak arc current is not very large but the fall time of the voltage is long (1600 nanoseconds) which accounts for the arc energy of almost 60 joules. Figure 2 is an XL4 klystron arc taken in an NLCTA modulator powering two XL4 klystrons. The modulator limiting impedance will allow the arc current to rise to four times klystron operating current, approx. 1600 amperes. During this arc the voltage fall time is faster and the current rise time slower. The current reaches a much higher

value but the voltage initially falls in

Figure 1. XL4 klystron arc on Test Stand 08
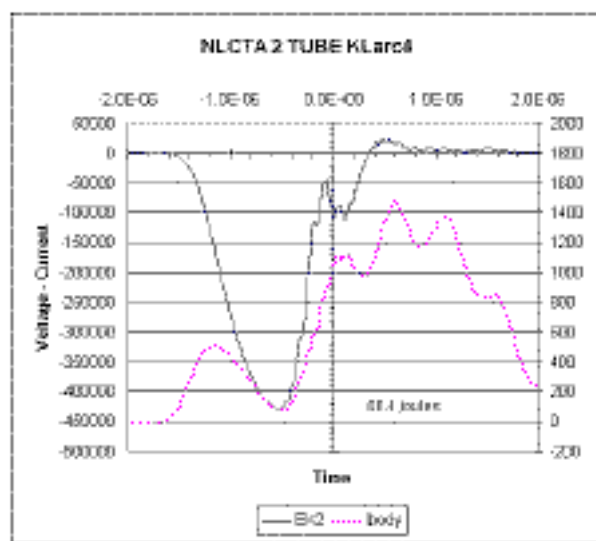
450 nanoseconds to 50kV and then falls to 0 volts in and additional 400 nanoseconds and the energy in the arc is about 60 joules. The arcs of Figures 1 and 2 are different in current and time but dissipate about the same energy. This data reinforces my belief that the arc formation is an unknown variable with some dependence on the external circuit.

The next version of the 75 MW PPM (periodic permanent magnet) focussed klystron, XP3 (formally known as the DFM klystron) is under construction. The XP3 Diode, a beam stick with a portion of the magnet stack has recently been initially tested in Test stand 13 at SLAC. This tube would nominally operate at 490 kV and

Figure 2. XL4 klystron arc in Two-tube Configuration

265 amperes. Figure 3 is a picture of an arc waveform captured while processing and operating this tube. In this case the arc causes the voltage to drop in 800 nanoseconds and the voltage essentially drops directly to 0. The current rises to almost 500 amperes in about 600 nanoseconds. This arc has a calculated energy of 42 joules. Two arcs were captured on this diode and both were about the same energy although different in waveshape. It should be noted that the XP3 electron gun has a microperveance of 0.75 and therefore has larger cathode to anode spacing than the XL4 klystron whose microperveance is 1.2. It is hard to relate the gap spacing in the electron gun to the rise of arc current or fall of arc voltage at this time. It should take ions longer to traverse the longer gap but there is a larger accelerating potential from the higher voltage.

Figure 3. XP3 Diode arc
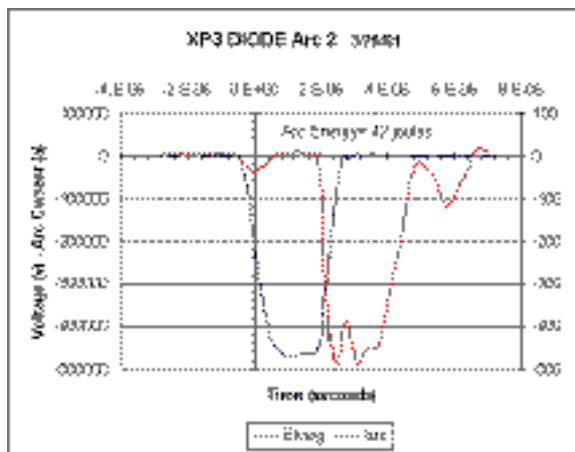
During modulator testing at NLCTA, a 5045 diode had a arc while operating above 400 kV. We have operated 5045's at this level in the past. However, this time, the 5045 diode would no longer hold voltage. Another diode was still in operation. The diode was returned to the tube shop for a careful autopsy. The arcing took place between the focus electrode and the bell housing near the high voltage seal joint. As can be seen in Figure 4, the stainless steel corona ring shows an area where thin layers of material have been removed. The second photo shows that material plated on the ceramic high voltage seal. This is the same area we have seen

ceramic seal punctures in the past. The gap between the corona ring and the ceramic is much smaller than the anode to cathode gap. We did not capture the arc that created the damage that we see. Obviously there is enough energy to ablate the surface material. In fact, it is most

probable that the damage did not all occur in one arc, but over a number of arcs. Perhaps some damage occurred during prior operation in another modulator. There was also activity on the anode.
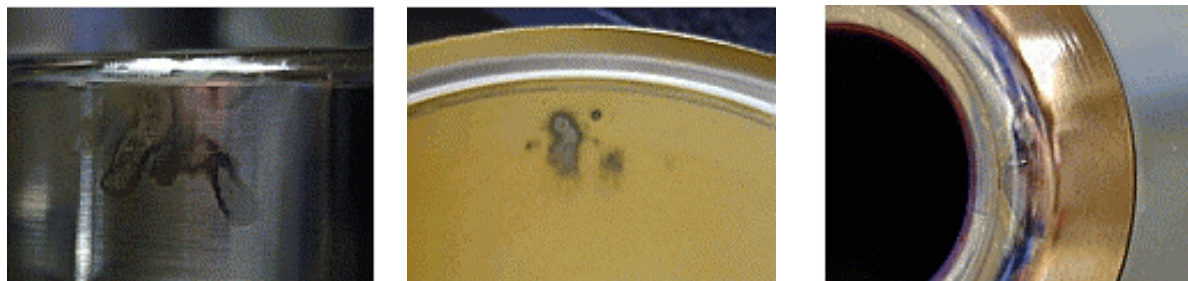

Figure 4. 5045 Diode Autopsy- Focus Ring (Upper left), H.V. Seal (Upper right), Anode (bottom)

3.2 Low Impedance Switch

3.2.1 10kV Marx Switch Modulator

Dr. Anatoly Krasnykh designed a modified Marx modulator for a TWT application at 10kV[2]. Although the voltage and power are much lower than the klystron modulators I was curious what the arc current would look like in this 'Direct Switch' modulator. Dr. Krasnykh made the following measurements with an air arc. The current sensing threshold was set slightly above the operating current and the measured delay in turn-off of the final switches was 700 nanoseconds. 400 nanoseconds was due to the gate delay of the IGBT itself. Figure5 are the voltage and arc current for arcs occurring at the beginning, the middle and the end of pulse.
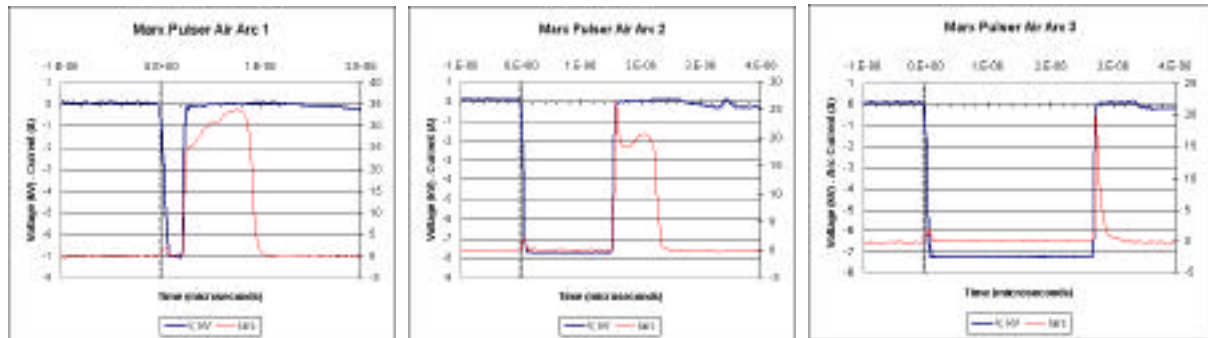

Figure 5. 10kV Marx Modulator Arc- 1) pulse beginning, 2) pulse middle, 3) pulse end

The normal operating load on the modulator was 1 ampere but the peak arc current rose to above 30 amperes. The energy is still low but what if this was extended to 500kV? Would the very high current create a problem or would the rate of rise be such that the voltage will be zero before the current reaches its very high level, thereby limiting the energy? These are unknowns that will only be answered by testing a full scale model. It is conceivable that testing of any of the low impedance 'direct switch' modulators would give enough insight to predict the performance of the others. Diversified Technologies has another SBIR grant to work on a direct switch modulator for 500 kV either with the modified Marx approach or a straight series switch.

3.2.2 Induction Modulator

The data on preliminary arcing into a vacuum gap below 80kV was not fully available at the time this paper was submitted.

4. CONCLUSION

Klystron protection in very high peak power modulators remains an issue that is still not clearly understood. Clearly, a klystron with excellent vacuum (8 to 9 scale), can dissipate more energy in a current limited gun arc than conventionally believed. However, recovering from an arc does not mean that some damage was not done. Surfaces do get electroplated with copper or stainless steel. All of the tubes tested had excellent vacuum in the gun region. We know that the low impedance modulators whether a Marx switch, an induction design or a hybrid with a pulse transformer have the capability of delivering larger peak arc current than a Line-type modulator. What we don't know is how fast the arc will build up and if the current will indeed rise faster or if the voltage will fall at a slower rate. These modulators can have the capability of terminating the pulse upon sensing an arc and depending on circuit speed can shut down the current. The only way we will know is to operate a klystron on these modulators. I am hoping that Diversified Technologies, Inc. will deliver a Hybrid Modulator built on an SBIR for testing at SLAC in the

fall. Dick Cassel and company is planning to have a full 500kV version of the induction modulator (affectionately known as the four dog) in test this summer. Therefore, I am encouraged that we should have a better picture of this phenomenon by the end of this year.

Further investigation is necessary to understand klystron arcs and how much energy causes damage. A demountable gun on a diode body would be required to enable examination of the gun electrode surfaces after a set number of captured arcs. The gun would then be reassembled, at least low temperature baked and re-tested.

ACKNOWLEDGEMENTS

REFERENCES

[1] S.L. Gold, "Thyratron-PFN, IGBT Hybrid and Direct Switched Modulator R&D as it Effects Klystron Protection", 2000 24th International Modulator Symposium, June 2000

[2] A. Krasnykh, etal.,"A Solid-State Marx-Type Modulator for Driving a TWT", 2000 24th International Modulator Symposium, June 2000

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