A THYRATRON FOR THE NLC BASELINE MODULATOR

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Abstract
There are several modulator techniques being investigated as candidates for driving NLC klystrons in groups of between two and eight per modulator. The baseline design is a conventional line type modulator that would use a thyratron as the switch to drive two klystrons. This paper describes a thyratron designed to meet these operational requirements. The target lifetime is 50,000 hours. Cost and reliability are of critical importance due to the large number of modulators required. Several design decisions were taken at the outset including cathode type, basic tube diameter and number of high voltage gaps required. The development process included measurement of cathode temperature as a function of average current and electrostatic field analysis of the high voltage geometry. The rationale underpinning the design that resulted is explained. Since the specification was first defined, the pulse width has been doubled with a corresponding doubling of the average current. The impact of this updated requirement on the existing design is also discussed.

1. INTRODUCTION

The table shows the original acceptance test criteria, operational data and the upgraded requirement as a result of the pulse width being doubled. The most significant challenge is to achieve the target life of 50,000 hours; all other parameters have been demonstrated to be well within the capabilities of modern thyratron technology.

Parameter	Original Acceptance Test	Original Operation	Present Operation
Anode voltage (kV)	90	75	75
Peak anode current (kA)	10	7.5	7.5
Inverse voltage (kV)	10 max	not known	not known
Di/dt (kA/us)	100	75	75
Average anode current (A)	2.5	2	4
Pulse duration (70%) (us)	2.2	2.2	4.4
PRF (Hz)	180	180	180
Jitter (ns)	1	1	1
Run time or life (hours)	24	50,000	50,000
Run time or life (shots)	1.55E+07	3.24E+10	3.24E+10

2. KEY DESIGN CONSIDERATIONS AND DESIGN DECISIONS

The work described here builds upon previous work [1,2] where the performance, life and suitability of various thyratron types and designs were discussed. The more recent paper [2] discusses data on the current life history of candidate tubes; it also identifies the optimum means of triggering and considers critical circuit parameters, which need to be considered to maximise thyratron life. These are considered in more detail here.

2.1 Cathode type

The thermionic cathode is one of the key features that will determine the achievable lifetime. The previous work indicates that the barium aluminate (BA) impregnated cathode size used for 4.5 diameter metal envelope tubes (e.g. CX1836 type) and the oxide cathode in the 6 diameter ceramic tubes (e.g. CX2410 type) are the minimum cathode sizes that could achieve 50,000 hours life at 2A average.

Field data supports this conclusion for Marconi Applied Technologies BA cathode tubes [2,3]. Insufficient field lifetime data exists for the Marconi 6 oxide cathode tube at high (≥2A) average current levels, but tubes of this type (CX2410) have been operational at KEK since 1995 at average currents from 0.3 to 1.3A [4]. Recent data from KEK [5] shows that out of the 16 tubes received in 1995 there have been three failures from poor connections to the cathode terminals and that the remaining operational tubes have accumulated an average service life of 17,000 hours to date (with a calculated MTBF of 85,000 hours!). There are lifetime data for thyratrons of this type from other manufacturers that indicate that several tens of thousands of hours are likely to be achieved under similar average current conditions. Since it appears that there is little difference emerging in service life between the BA cathode in the 4.5 tube and the oxide cathode in the 6 tube, the oxide cathode is preferred over the smaller BA counterpart simply on the grounds of cost.

2.2 Reservoir type

A high capacity reservoir system has been selected so that gas pressure adjustments throughout tube life are minimised. The high capacity system is more complex than a conventional reservoir; there are two reservoir capsules which operate at different temperatures and further auxiliary control components to compensate for input power fluctuations and ambient temperature variations. The total gas content, however, is typically more than ten times greater than that of a typical conventional reservoir. This large capacity has the significant added benefit that the need for reservoir ranging to compensate for gas clean-up losses is removed.

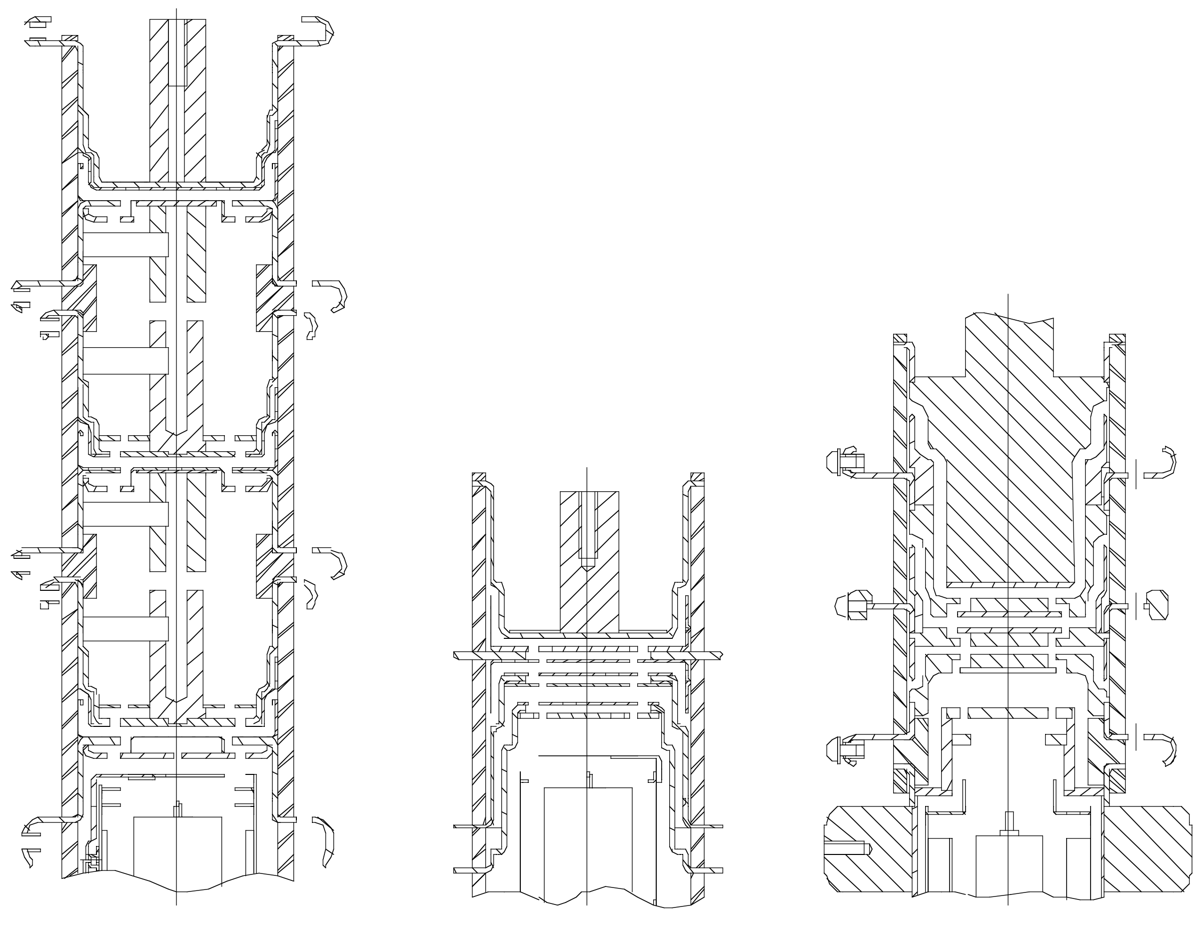
2.3 High voltage structure and number of gaps

Previous work [1,2] has indicated that a minimum of three high voltage gaps are required for reliable operation at 75kV under command or resonant charge conditions. Two basic mechanical designs of multi-gap tubes exist as shown in Fig. 1. Fig. 1a is the stackable, repeatable, drift-space structure and Figs.1b and 1c are examples of two and three gap nested-cup structures, respectively. On a parts count and therefore cost point of view, a design like Fig. 1b or 1c is preferred.

2.4 High voltage structure materials

Traditionally, very high voltage structures have been faced with molybdenum because it has proved more resistant to arcing than copper, especially at anode voltages above about 60kV. High voltage structures above this level using copper have been built before but have tended to exhibit destructive arcing. An inherent property of all multi-gap thyratron structures is the very high peak transient electric fields that occur as a consequence of the way the tube commutates. The tube is triggered at the cathode end and the high voltage gaps go into conduction starting with the gap nearest the cathode, followed by a delay of around 50 ns before the next gap, and so on. The result is that the last high voltage gap at the anode must withstand the full anode voltage for a period of around 50 ns without arcing. Molybdenum appears to become electrically conditioned to withstand this (tubes have been operated successfully at up to 160 kV) but copper has been observed to suffer arc damage that prevents this conditioning from occurring. Despite this, copper would be preferred on the grounds of cost and since cost is such an important factor, the design of the high voltage structure was undertaken on this basis. This represented a risk worth taking.

Fig. 2 is a field plot of a simplified representation of the top gap of the proposed prototype design and shows that there is peak electric field of around 13.6 kV/mm when a potential of 30 kV is applied. With an applied anode voltage of 90 kV corresponding to the specification maximum, these figures are exceeded by a factor of three for a period of 50 nsec or so during commutation. Although the field during commutation is rather high at around 40 kV/mm, it is only a transient field. The limits for acceptable peak field strength under such transient conditions are not precisely known, but test results presented below indicate that they have not been exceeded in this instance. The radii of curvature on the selected geometry are larger than those previously utilised for copper high voltage geometries as a result of the results obtained by undertaking the field plotting work. The generally accepted maximum field strength for d.c. applied voltages in electron tubes with conditioned surfaces is around 10 kV/mm. The field strength in the top gap with 25 kV applied (corresponding to the 75 kV operating level) is around 11 kV/mm, but this field will only be present for a small fraction of a second. The significant magnitude of the transient applied peak fields can be reduced using a relatively simple circuit technique, as discussed next.



(a) (b) (c)

Fig. 1 Various thyratron high voltage structures. Fig. 1(a) is a typical example of the stackable drift-space multi-gap structure, whilst figs. 1(b) and 1(c) are typical examples of two- and three- gap nested-cup geometries.

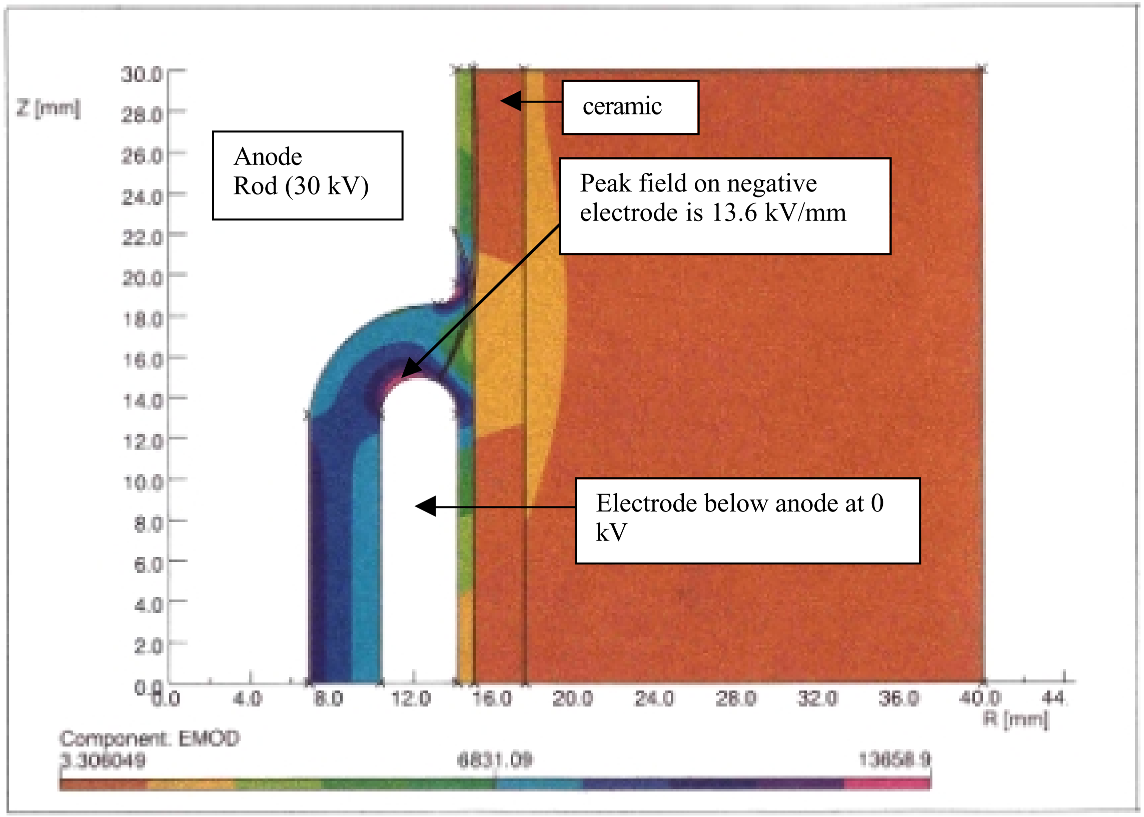


Fig. 2. Electric field plot of the critical area within the proposed top gap geometry. The z-axis represents the axis of the thyratron . Also shown are the trajectories of single electrons released from the surface of the electrode below the anode.

2.5 Saturating anode inductor

To reduce the anode heating arising from switch-on losses, and, more important in the light of the above discussion, to reduce the voltage appearing across the top gap during thyratron commutation, it is proposed to use a saturating anode inductor with this tube design. Detailed work performed at CERN [6] indicates that a saturating anode inductor with a volt-second product of 1.6mVs will give a switch-on delay of approx. 70ns with a three gap of the drift space design and that this will prevent any excess voltage build up across the top gap of such a tube. Shorter delays will offer proportionately less protection and it may be necessary to trade off the effect of the added saturated inductance on the current rise time against the protection afforded to the top gap. Saturating anode inductors also afford some protection against the adverse effects of inverse voltages [7].

3.0 FINAL PROTOTYPE DESIGN

The design that was selected for manufacture is shown in Fig. 3. The key features outlined above are incorporated: an oxide cathode from a 6 diameter thyratron, a high capacity reservoir system, copper electrodes and a nested-cup high voltage structure. The tube envelope surrounding the cathode structure uses copper in preference to the more conventional ceramic and the basic diameter of the control grid and high voltage structures is 4.5 rather than 6 . These features result in a hybrid design that is tailored specifically for this application where cost, reliability and operating lifetime are paramount.

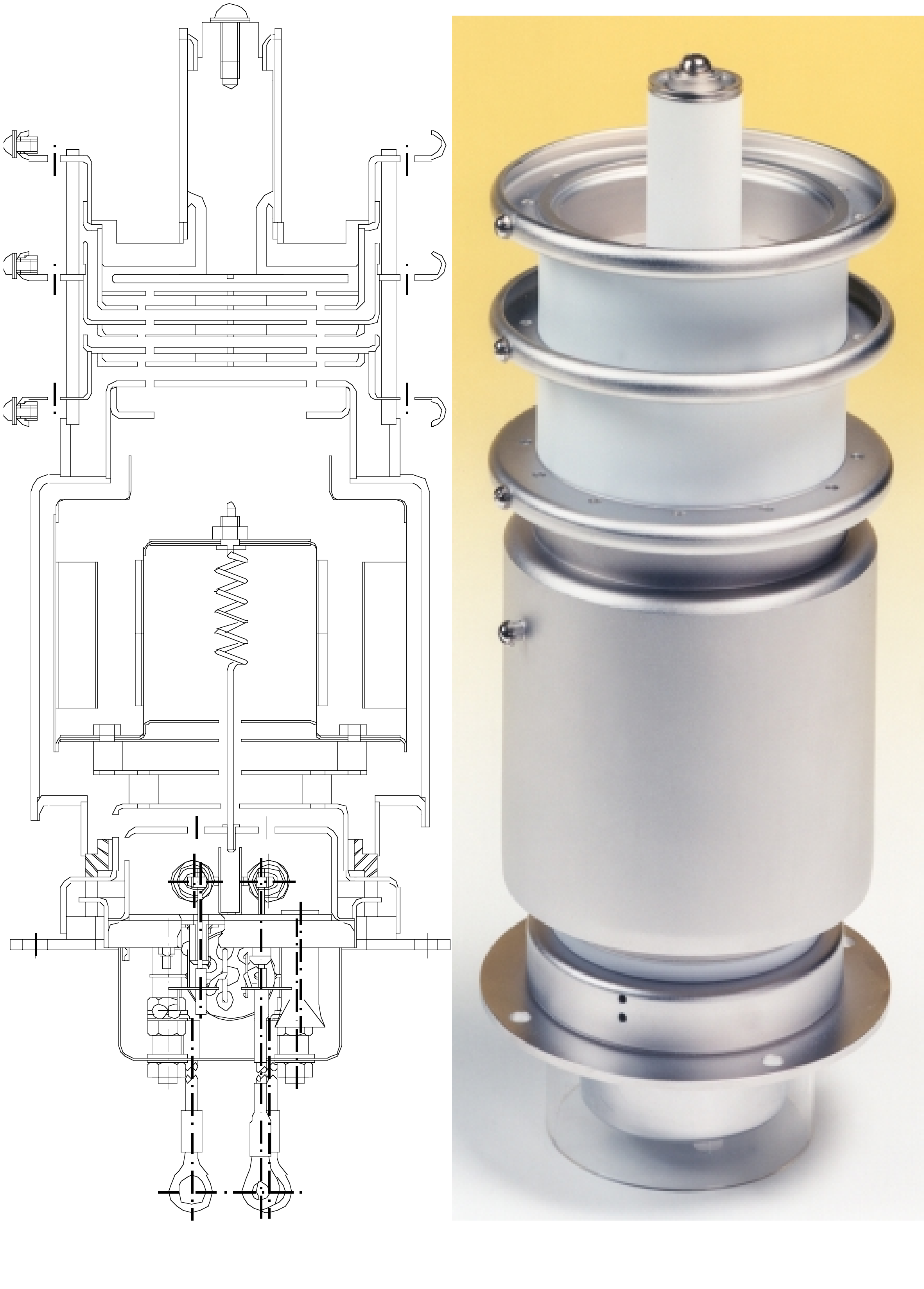


Fig. 3 Drawing and photograph of final CX2437X design for 2A average current operation

4. FACTORY MODULATOR TESTS

4.1 Cathode Temperature Measurement

The optimum cathode operating temperature is a balance between sufficient primary electron emission at one extreme and minimising thermal evaporation at the other. Drawing from experience and published data [8], this temperature lies somewhere in the range 750-780 ^{O}CB. Thyratrons differ from all other electron tubes in that cathode back heating by ion collection/impact will make a significant contribution to overall cathode power dissipation. A sample tube was manufactured with a sidearm window to enable cathode temperature to be measured with an optical pyrometer and fig. 4 shows the measured cathode temperature against average current for the first CX2410 cathode design. It can be seen that the quiescent non-operating cathode temperature is at the top end of the acceptable range and that the temperature climbs significantly as the average current switched is increased (by increasing the prf). Fig. 5 shows how cathode temperature varies with input heater power alone, from which it is deduced that the optimum input power is around 450W to achieve 750 ^{O}CB. This equates to a heater current of 71A at 6.3V and the cathode heater incorporated into the design was selected to have these parameters.

Given that a temperature difference of as little as +25 ^{O}C may double the rate of coating evaporation [9] the importance of getting the temperature correct is evident. Given this, it is perhaps surprising that the practice of operating thyratrons with reduced heater power to compensate for back-heating has not been adopted much more widely. The data in figs. 4 and 5 allow calculation of the required reduction in cathode input heater power to maintain the cathode at the optimum temperature for operation at a given average current.

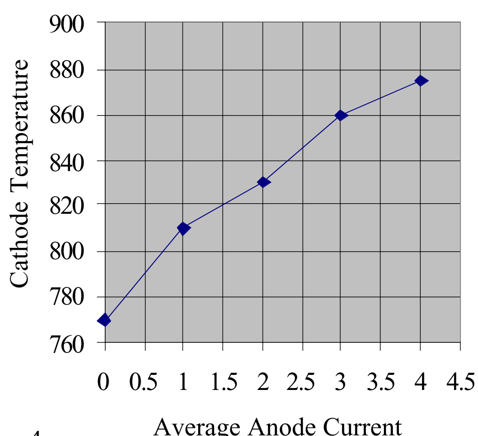


Fig. 4 Cathode Temp. (^{O}CB) vs. Average Current

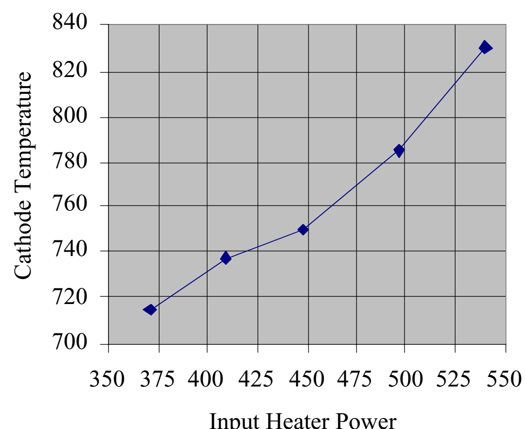


Fig. 5 Cathode Temp. (^{O}CB) vs. Input Heater Power

4.2 High Voltage Operation

Marconi Applied Technologies does not have equipment to test an NLC tube under all conditions simultaneously, but there are separate equipments that can test groups of parameters that collectively encompass most aspects of the specification. The high voltage tests performed on two prototype tubes are summarised below. Both tests were carried out with a saturating inductor giving a switch-on delay of about 18ns (Ferrite type CMD5005, 4 OD, 2 ID, 1 thick) [10].

i) 85kV, 2.83kA, 0.6us pulse in a command charged (2ms with a 8ms hold), fast rate of rise of current (120kA/us) equipment, but at only 5Hz.

ii) 70kV, 10kA, 6us pulse at up to 67Hz (4A average) in a resonant charged, slow rate of rise of current (8kA/us) modulator.

Fig. 6 is an oscillogram of the anode current rise at 85kV with a reasonable gas pressure in the tube: 10-90% risetime, including the overshoot, is 28ns, which gives a di/dt of 101kA/us. Jitter is 0.9ns peak-to-peak.

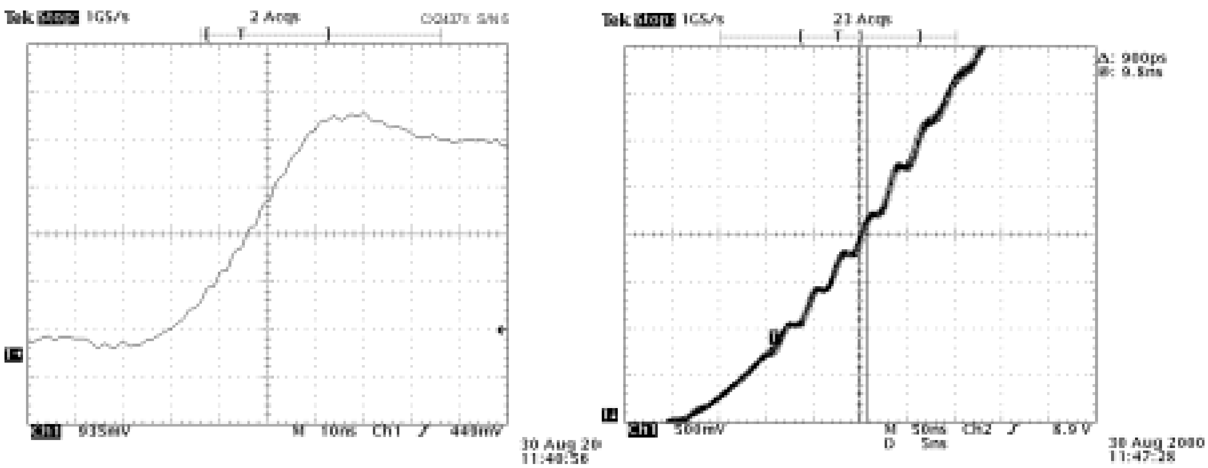


Fig. 6 Anode Current rise-time and Jitter

Under high average current conditions in the 70kV modulator, the two prototype tubes, denoted with type number CX2437, operated flawlessly. One of the parameters measured was the rate of fall of anode voltage, commonly called the dv/dt signal. The dv/dt signal provides a relative measurement of the gas pressure in the high voltage structure. Fig.7 shows the variation of the dv/dt signal as the average current is increased (by increasing the prf) for the two CX2437 tubes. For purposes of comparison, similar data is shown for the CX1536, which is a standard product used commonly in high power linacs of various types. It can be seen that the CX2437 thyratrons display a larger gas pressure variation than the CX1536 as average current is increased. For operation at the 2A average current condition of the original specification, the performance of the CX2437 design is deemed to be well within acceptable limits. The difference between the performance of the CX2437 and the CX1536 is attributed to improved heat extraction from the surface of the anode due to the larger diameter anode rod in the latter. The average cross sectional area of the CX2437 anode rod is only 16% of that of the CX1536.

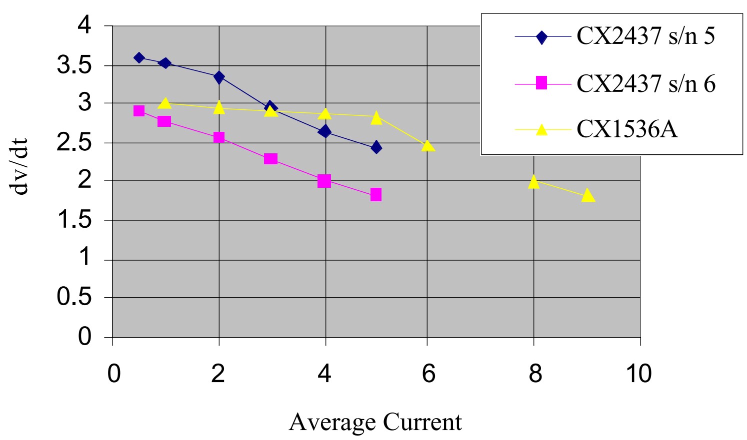


Fig. 7 Dv/dt signal with average current

With a pre-pulse of 10A on the grid 1 and a 0.5us delayed trigger pulse to the control grid 2, CX2437 jitter was around 0.9ns peak-to-peak under both sets operating conditions used in the factory tests and therefore within limits. If needs be, the jitter could be reduced further by using dc power supplies to energise the cathode heaters or by increasing the rate of rise of voltage supplied by the control grid 2 pulse generator.

5. DEVELOPMENTS TO MEET THE LATEST SPECIFICATION

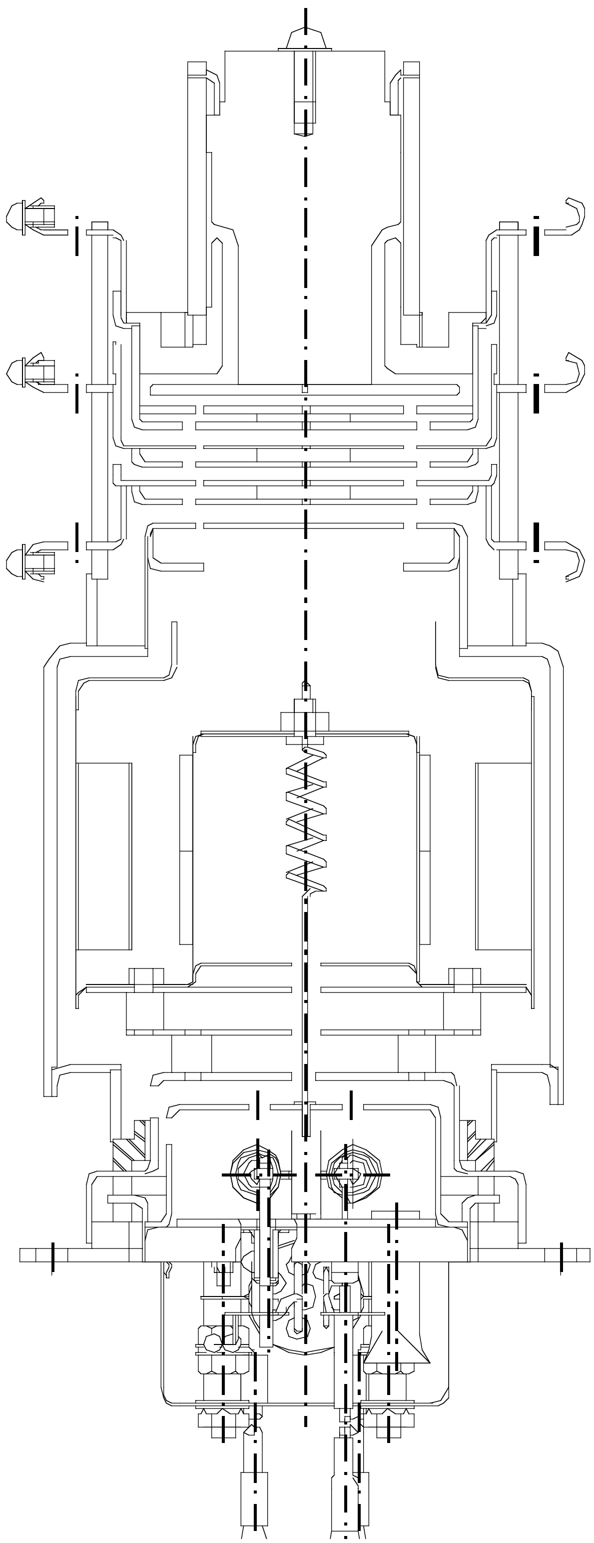


Fig.8 Thyatron design with larger anode.

Fig.7 shows that the doubling of the average current to the 4A level causes a significant fall in the internal gas pressure within the high voltage structure. This can be overcome simply by improving the heat extraction i.e. by incorporating a larger diameter anode rod. Fig. 8 shows a proposed modification where the anode rod has an average diameter approximately four times that of the two prototype samples. It is anticipated that such a tube would exhibit performance similar to that of the CX1536 in fig.7 at up to 4A average current. There is also scope within the existing envelope to incorporate a cathode with a significantly larger surface area, although the figure does not depict this. A larger cathode would be necessary to maintain the 50,000 hours target life in light of the cathode back-heating increasing significantly at double the pulse width.

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