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FAK PROJECT HIGH-VOLTAGE FAST SWITCHES

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1. GENERAL

1.1 Introduction

The high-voltage pulse switching of the FAK is achieved with thyratrons which have been carefully mounted in low inductance coaxial housings. The rise-time of the current pulse in each FAK module magnet is determined by the switching performance of its associated thyratron switch, termed the "Main Switch", which is located at the front end of the cable PFN. The fall-time of the magnet current pulse is determined by the switching performance of a second thyratron switch, termed the "Dump Switch", which is located together with a matched terminator at the remote end of the cable PFN.

This system of double-ended switching of the cable PFN permits stepless variation of the magnet pulse length from zero to that determined by the length of the cable PFN. This pulse length variation is achieved by differential timing of the switching instants.

A simplified schematic diagram of a single FAK module pulse generator is shown in Fig. 1. All modules are identical.

1.2 General electrical construction

Both the main and dump switches employ the ceramic enveloped thyratron CX1171A of English Electric Valve Co. manufacture. This tube is mounted with floating cathode in the case of the main switch and with grounded cathode in the case of the dump switch. In order to obtain a low switch inductance the tube is mounted in a fairly close-fitting earth return cylinder, the insulation between tube and cylinder being a mixture of solid (epoxy) and liquid (transformer oil) dielectrics. Tube heater, reservoir and grid supplies are derived in both cases from air-mounted "Faraday cages" -- in the case of the main switch this cage has to be insulated to withstand at least the full magnet pulse voltage to ground.

The switching system is completed by a significant quantity of rack-mounted electrical and electronics equipment, located at some distance (≃ 10 m) from the actual switches. This equipment serves to provide the tube auxiliary supplies, the trigger pulses and embodies the comprehensive protection system which limits tube malfunctioning.

1.3 General mechanical construction

The main switch and dump switch are separate mechanical assemblies. Both must be oil-filled under vacuum (see notes on oil pumping equipment MPS/AE/Note 74-2). Both switches embody araldite interfaces which separate the switch oil from the PFN SF_6, the latter being at 9 atm pressure.

The dump switch is mounted in a combined assembly with the so-called dump resistor and the high-voltage portion of the pulsed resonant power supply which recharges the cable PFN.

2. THYRATRON CHARACTERISTICS

2.1 Development work

The development work on hydrogen thyratrons as high-voltage switches was reported by Grier in MPS/SR/Note 69-22. This report remains fully valid in the light of subsequent operating experience. It should be referred to for a full understanding of the processes involved in thyratron switching, which are not repeated here.

2.2 CX1171 construction

The CX1171 is a deuterium-filled, three-gap high-voltage thyratron having a ceramic/metal envelope. It may be oil-immersed in any mounting position. The cathode is oxide-coated and indirectly heated. The gas reservoir is titanium hydride, which is heated by an independent heater from that of the cathode.

The CX1171 belongs to the tetrode series of tubes. Its first grid, known as G1, preionizes the cathode-grid region. The second grid, known as G2, performs the gating function.

In addition to the grids G1 and G2, two further gradient grids are provided on the CX1171. These gradient grids serve to apply equal voltages to the three series gaps of the tube, an external voltage divider providing the necessary voltages. Further it should be noted that each of these gradient grids consists of two electrodes which must be bridged by 2 × 270 Ω resistors in series. Two separate resistors are necessary, because of the physical disposition of the electrodes and the need to avoid distortion of the voltage gradient over the tube ceramic. These two electrodes are at the same potential except for the brief instant of current rise or fall in the tube.

2.3 CX1171 performance

In both main and dump switch applications the CX1171 is able to withstand safely an anode voltage of 80 kV when the reservoir heater voltage is correctly adjusted. The adjustment of this voltage is critical -- if it is too high the tube will not hold off the anode voltage and if it is too low there is a serious danger that the normal plasma discharge in the tube will change to a spark breakdown between some or all the tube electrodes. This latter condition must be avoided at all costs as it leads very rapidly to complete failure of the tube.

When the reservoir heater voltage is correctly set the CX1171 has a typical pulse rise-time into a matched 15,0 Ω load of 30-34 nsec (taking a definition of rise-time as the time for the current to increase from 10% to 90% of its final flat top value). Increasing the reservoir heater voltage shortens the rise-time. Finding the correct reservoir heater voltage for each tube is a matter of trial and error -- the actual value for correct operation varies significantly from tube to tube due to the different weights of hydride included in the tube reservoirs. When trying to find this correct setting for the first time it is most important not to start with too low a reservoir heater voltage as this may be causing internal sparking and destroy the tube in a very short time. Guidance on the correct setting is available from the test certificate, provided with each tube, relating to tests at Chelmsford in a CERN-loaned dump switch housing.

The pulse rise-time of 30-34 nsec is more than adequate for the excitation of the FAK module, there being a margin of approximately 15 nsec in the magnet field rise-time with respect to the bunch-bunch interval. Therefore some deterioration of the pulse rise-time in service is acceptable, subject always to the avoidance of the spark mode of operation.

The nominal heater voltage of the CX1171 tube is 6.3 V. However, for low pulse repetition rates (which is the case for the FAK application) the manufactures recommend (even require) that this be raised to approximately 6.8 V. The filament warranty of 5000 h remains valid. The heater voltage, measured at the tube tail wire, is approximately 6.7 V for all sockets of the FAK system.

Successful CX1171 performance depends on the correct grid supplies. The tube has two independent control grids, called G1 and G2. G1 is used for pre-ionizing the cathode-grid region and G2 is the trigger grid. Two methods are allowed for the excitation of G1, one a pre-pulse on the trigger pulse of G2 and the second by the application of a d.c. voltage. All FAK tubes adopt the second solution; it has the advantages of limiting the possible damage from spontaneous firing and permits monitoring not only of the G1 supply, but also the heater and reservoir heater supplies. The d.c. G1 current employed on FAK tubes is nominally 100 mA. The trigger grid G2 must be biased negatively to maintain the CX1171 non-conducting. Switching action results from attacking G2 with a low jitter fast rise-time pulse, normally of about 1.5 kV unloaded amplitude. Both the main and dump switches are triggered in a similar manner, via an inverting transformer for the G2 pulse.

The CX1171, for a given reservoir heater voltage setting, will switch over a very wide voltage range (say 10 kV to 80 kV). However, the foregoing figures for rise-time relate to 80 kV, the nominal fixed FAK operating voltage. Nevertheless, variation of anode voltage in the range of 40-80 kV is permitted for FAK operation and is foreseen in the settings adopted for certain protective devices. Any changes of anode delay time resulting from such changes in anode voltage are automatically compensated by hardware in the control racks (drift stabilizers).

3. MAIN SWITCH

3.1 General

The purpose of the main switch is to connect the 15 Ω SF_6 pressurized Câbles de Lyon PFN cable to the twin parallel 30 Ω coaxial transmission cables leading to the magnet. If the PFN is charged to 80 kV then the switched pulse amplitude is 40 kV.

The mechanical construction is shown in assembly drawings MPS 2A20-551-0 or MPS 2A20-552-0. The explanation for two alternative assemblies lies in the fact that the design of the HT lead-in, which is also the SF_6/oil interface, was modified because of manufacturing difficulties. Some modules were, nevertheless, constructed according to the original design (2A20-552-0). All later modules and all spare parts are constructed according to 2A20-551-0.

The electrical schematic of the main switch assembly is given in drawing 2A32-926-2. Its "Faraday Cage" circuit diagram is MPS 2A32-927-3.

3.2 Mechanical construction (2A20-551/552 refer)

The CX1171A tube is lodged in the coaxial housing 2A20-402-1A. The anode end of this housing is closed by the HT lead-through which also acts as the SF_6/oil interface. Two executions of this interface exist; early switches are built up from parts 2A20-403-3, 2A20-404-2A, 2A20-405-2; later switches and spares are built from parts 2A20-553-3, 2A20-404-2A and 2A20-554-2. The new and the old interface assemblies are fully interchangeable. The gas-filled PFN cable is connected to this interface by flange 2A20-406-2A, which also contains a capacitive pick-up ring which can be used for diagnostics. This ring is not so used in the FAK installation, but can be employed in times of difficulty when additional information is required. Note that this pick-up must always be terminated in 75 Ω. The cathode end of the tube housing is connected to hollow block 2A20-401-0. This block is closed with 3 covers; the lower cover 2A20-454-2A contains the two LEMO high-voltage sockets for the pulse transmission cables, the top cover 2A20-444-2 is a simple blanking plate and the side cover 2A20-429-2 serves both as a blanking plate and the mounting for the capacitive pick-up used in the CX1171 protection circuits.

(It should perhaps be pointed out that historically the main switch was developed as a double switch, permitting the sequential discharge of two cable PFN's into a single load. For this mode of operation cover 2A20-444-2 was removed and replaced by a second thyratron housing 2A20-402-1A. A reconversion of the FAK equipment to this mode of operation still remains technically possible for the switchgear as installed in B359.)

Tank 2A20-413-0 is bolted to the housing 2A20-402-1A and communicates with it through an elongated hole running the full length of the CX1171A tube. This tank serves as the location of the following important electrical equipment: (i) isolating transformer 220/220 V 350 VA for supplying Faraday cage, (ii) trigger pulse transformer 2A20-700-4, (iii) CX1171 voltage divider 2A20-440-2 (iv) grid 2 filter block 2A20-435-3. Electrical connections are made with the externally-mounted Faraday cage 2A20-445-1 via the multiconductor lead-through 2A20-408-2. Electrical supplies for the tube base return from this Faraday cage via 2A20-408-2 and 2A20-412-2. The voltage divider 2A20-440-2 is connected to tapped lugs on the CX1171 via insulated flexible columns 2A20-438-4 -- there are two lengths, long columns (130 mm) being used for gradient grids 1 and 2 and short columns (125 mm) being used for the anode, G2 and the cathode. Standard RG59 cable and fittings are used to connect the primary and secondary of the pulse transformer -- care must be taken with the length and route of the secondary side cable as this jumps to full pulse potential with respect to ground.

The main pulse current is fed to the outgoing LEMO sockets via two demountable brass blocks 2A20-426-3 and 2A20-443-3.

The switch is inclined at 15° to the horizontal. This is in order to ease the problems of connecting the very rigid PFN cable to the switch anode and to ensure that air bubbles cannot collect at the anode in the event of malfunctioning of the oil-cooling system.

The switch must be filled under vacuum (see MPS/AE/Note 74-2, page 15). Under normal service conditions pressurized oil (approximately 3 ℓ/min) is fed via cover 2A20-429-2 into block 2A20-401-0. From here the oil is directed onto the cathode flange of the tube, escaping via the RF contact of 2A20-409/410-3 and via small holes in the araldite insulator 2A20-407-2. The heated oil then passes into the tank 2A20-413-0 from which it returns to the oil reservoir via a tube mounted at the tank top.

The externally-mounted forced air-cooled Faraday cage is mounted on steatite insulators of sufficient length to withstand the full pulse voltage. The cage is surrounded by a protective metal cover with small plexiglas front window for meter observation, 2A20-417-1. This cover is attached to tank 2A20-413-0 by 10 hexagon-headed M6 bolts. This is for electrical safety reasons as under no circumstances must this cover be removed when the equipment is operational. The cover is provided with a long nylon adjuster 2A20-451-4 which engages with the control potentiometer for the reservoir heater voltage of the Faraday cage. Again for safety reasons this adjuster must not be removed if the equipment is operational.

3.3 Electrical circuit (2A32-926-2 refers)

The anode end of the switch is insulated for 80 kV pulsed low frequency resonant charging, i.e. basically insulated for 60 kV r.m.s. 50 Hz.

The cathode end of the switch, which includes the trigger pulse transformer and the Faraday cage is insulated for 60 kV peak, short duration pulses (not exceeding a few microseconds). In consequence, great care must be exercised to ensure that the full PFN charge voltage is never applied to the cathode region of the tube. This risk is avoided if the transmission lines and a 15 Ω terminator are always connected to the cathode -- operation without such a load is expressly forbidden. However, in order to limit still further the risk of such mal-operation a 370 kΩ safety resistor is included from cathode to ground. This ensures, together with the voltage dividing resistors R1-R6, that the PFN charging voltage which appears at the cathode is still acceptable in the event of failure of the external 15 Ω load.

Under normal conditions the PFN charging voltage is distributed equally across the 3 tube gaps by R1-R6, each of 7 MΩ. This value is chosen such that minimal distortion of the voltage division occurs due to the differential capacitance to ground of the various gaps for PFN charging times of the order of 4 msec. The voltage divider R1-R6 is adequately rated to withstand full PFN voltage for at least 30 msec at each charging cycle. However, it is not rated to repeatedly discharge to zero the PFN after each charging cycle. It is therefore important that the PFN be discharged via the main and/or dump thyratron and not left to decay exponentially via R1-R6 (an automatic system is included in the dump switch for this purpose -- see Section 4).

Attention must be drawn to the CX1171A gradient grids. These are two electrode devices which in the FAK application are bridged by two wire-wound series resistors of 270 Ω. The two electrodes of a gradient grid are at the same potential, except during the switching instant. The precise role played by the 2 × 270 Ω resistors is not clear but their importance for satisfactory operation is established.

Two electrical components, mounted within the oil tank 2A20-413-0, which are worthy of note are (i) the Mullard FX1478 ferrite ring on the G1 supply lead and (ii) the G2 filter block 2A20-435-3. The role of the former is to despike the G1 circuit of the external Faraday cage from voltage transients when switching, or more particularly in the event of CX1171A spontaneous breakdowns. The G2 filter block serves a number of purposes -- firstly it permits the addition of the negative G2 bias level and the positive trigger pulse; secondly it provides a reasonable terminating impedance for the trigger pulse transformer; thirdly it provides the correct G2 forward impedance, and fourthly it despikes return pulses from G2 at the switching instant.

The pulse trigger transformer 2A20-700-4, also mounted in tank 2A20-413-0, is a 1:1 isolating and inverting transformer. It has a ferrite core and electrostatic screen between its 18 turn primary and secondary windings. Typical input pulse waveforms are included in each module test report, available in B359.

The externally-mounted Faraday cage 2A20-445-1 serves the role of protecting the low-voltage components of the thyratron supply circuits from differential voltages when the cathode/grid region jumps to full pulse voltage. In principle, the cage itself may be pulsed to any voltage level without producing a voltage gradient within the cage. The cage is air insulated from ground and has rounded edges and corners to reduce local electrical stresses.

The Faraday cage circuit is shown on 2A32-927-3. Transformers T1, T2 and T3 are supplied at 220 V on the primary by the secondary of the 350 VA isolating transformer, which in turn is supplied from a 220 V Philips stabilizer. The output of T1 (80 V r.m.s.) is rectified and smoothed by D1 and C2 to provide 100 ± 10 mA which preionizes the CX1171 via the G1 current meter M3, R5 and a 24 V 3 W lamp, which when lit closes the G1 interlock via a photo cell. The 150 V output of T1 is rectified and smoothed by D2 and C3 to provide 200 ± 30 V negative bias to G2 via the trigger pulse transformer and the G2 filter block. T2 is the CX1171A reservoir heater transformer and supplies this heater with a voltage which is adjustable between 5.4 and 7.0 V r.m.s. The adjustment is made by the variable primary taps 220, V2 and V3 (minimum output voltage is obtained with the primary tap V3) and the variable resistor in the primary circuit, which is mechanically coupled to the exterior of the protective cover 2A20-417-1 by insulated rod 2A20-451-4. T3 supplies 23 A at 6.8 V r.m.s. nominal to the CX1171A heater.

The capacitors C1, C4, C5, C6, C7, C8 and C9 are protective capacitors, intended to integrate to low levels any voltage spikes developing on the heaters or grids during the early stages of CX1171 conduction.

Connections between the Faraday cage and other parts of the electrical circuit are by "multicontact" male/female pins. These are size-graded to prevent the possibility of cross-connection.

The reservoir heater voltage (generally termed "reservoir voltage") is monitored on M2, an a.c. voltmeter with expanded scale and suppressed zero. Meter M2 is always calibrated against a standard meter (Gossen) at 5.5 V. The heater voltage is monitored on M1, a 0-10 V a.c. meter. Grid 1 current is monitored on M3, a 0-150 mA d.c. meter.

3.4 Protection

Protection is provided which stops the module in the event of either cooling failure or electrical malfunctioning.

Cooling protection is provided by an oil flow relay which trips the high-voltage power supply if the main switch oil flow falls below about half its normal flow of 3 ℓ/min. There is no oil temperature protection, other than that for the entire oil cooling system at the oil pump.

Comprehensive electrical protection is provided as detailed below:

i) Warm-up time interlock.
ii) Grid 1 current interlock.
iii) Faulty shot (or spontaneous breakdown) interlock.
iv) Drift stabilizer interlock.
v) Pulse length comparator interlock.

A FAK module may be pulsed only when it is in the ON state. A time delay is incorporated which prevents pulsing until the tubes have had sufficient time to warm up. The delay from OFF to ON states is 15 min. A STANDBY state is also provided whereby the module CX1171A tubes are heated at reduced filament and reservoir voltages (≃ 10% down). The delay from OFF to STANDBY states is 15 min with a further delay from STANDBY to ON states of 2½ min.

The grid 1 interlock is a photo-cell which is excited by a lamp mounted in the Faraday cage. Failure of the G1 current trips the HT power supply, preventing further PFN charging. The G1 interlock is intended primarily to detect failures of the tube heater or reservoir heater and their respective power supplies. G1 current ceases after some cooling-down delay if the heater or reservoir heater are without supply.

The faulty shot interlock employs the capacitive pick-up signal from flange 2A20-429-2. The coincidence of this signal and the thyratron trigger signal is checked in the "Thyratron Protection Unit". Pick-up signals occurring without an associated trigger are counted as "faulty shots". The electronic chassis provides variable warning and trip levels and counting facilities.

The same capacitive signal from 2A20-429-2 is used for the CX1171A drift stabilizer. This is a device which compares the instant of arrival of the pick-up signal with a fixed time arbitrary reference pulse. Any difference is due to variation of firing delay of the CX1171. The drift stabilizer corrects this variation on a step-by-step basis on succeeding cycles. The maximum step correction is ±5 nsec. The drift stabilizer is able to work over a correction range of about ±100 nsec total. If it is required to make corrections outside this total then it gives a trip signal to the HT power supply; this is known as a "Drift Stabilizer Warning Interlock". This protection serves many purposes as it is an overall monitor of correct pulse timing with respect to the trigger. It thereby confirms the presence of a correctly timed pulse at the main switch cathode.

The pulse length comparator (PLC) interlock again makes use of the capacitive pick-up signal from 2A20-429-2. This is compared against a signal from the magnet terminating resistor. Any discrepancy of pulse length exceeding 50 nsec indicates a high-voltage breakdown, either in the transmission system or in the magnet. The electronic chassis provides variable warning and trip levels and counting facilities. This interlock is of particular importance, because in the event of breakdown in the magnet or its transmission the dump thyratron is required to pass reverse current which can rapidly damage it. In consequence the PLC trip level must be kept low (normally 1 count maximum)..

3.5 Dismantling and rebuilding instructions

3.5.1 Safety

It is possible to dismantle one main switch whilst the others continue to pulse into the magnet. However, the following safety precautions must be observed.

i) The module must be isolated by opening its main isolator at the top of the staircase leading to the main switch gallery. The key must be removed and retained by the person carrying out the work.

ii) All primary electrolytic capacitors of the module on which it is intended to work must be fully discharged. Automatic discharge circuits are incorporated; voltmeters are provided on each capacitor unit for the verification of the discharge.

iii) The pulsing of all modules must be interrupted in order to withdraw the two LEMO plugs from flange 2A20-454-2A. When removed these plugs must immediately be capped with the brass safety covers provided and the locking screw of the LEMO plug retightened.

iv) After the action of (iii) has been completed the pulsing of the remaining modules may be restarted.

The module which has been isolated is now safe to work on. The internal voltage dividers of the two CX1171A tubes (main and dump) ensure that the PFN is discharged to ground. However, the first contact with the HT components after opening must always be made with the earthing stick provided.

Because FAK is a multimodular system, great care must be exercised in working on only that module which has been correctly isolated. The main isolator key number must correspond to the number of the module being worked on. Failure to respect this rule can be fatal -- the recharging time to 80 kV is only 4 msec and the energy unlimited.

3.5.2 Removal of CX1171A

i) Drain the switch oil by opening the bypass valve V_{BP}, closing the inlet and outlet valves V_I and V_O and opening the drain valve DV (refer to colour code for valve identification). Open vacuum valve VV. Allow the switch to drain into the drain tank -- approximate time 30-45 min.

ii) Place oil drip tray below switch to catch oil trapped in components when removing.

iii) Remove flange 2A20-429-2.

iv) Remove 2 × M10 × 80 bolts securing 2A20-443-3 to 2A20-426-3.

v) Remove flange 2A20-454-2A complete with 2 LEMO sockets, coupling piece 2A20-455-3 and brass block 2A20-443-3.

vi) Remove brass block 2A20-426-3 from the RF contact 2A20-409-3.

vii) Remove cover 2A20-414-3 from tank 2A20-413-0. Carefully retain tube identification tag fitted under one of the retaining bolts.

viii) Remove assembly 2A20-440-2 after first removing plexiglas cover 2A20-434-4 and disconnecting electrical connections to filter block 2A20-435-3. Note that 2A20-440-2 is fixed to 2A20-431-1 by 4 nylon screws.

ix) Unscrew the flexible columns 2A20-438-4 and retain in order for re-installation. Note columns are of different lengths.

x) Raise the conductor block 2A20-412-2 after slackening the pinch bolt in clamp 2A20-416-4 and removing the electrical connections from the top. At the same time the CX1171A tail wires must be removed from the lower end of 2A20-412-2. Raise 2A20-412-2 until it clears the vetronite cylinder of 2A20-407-2. Retighten the pinch bolt to retain 2A20-412-2 in the raised position.

xi) Remove the M4 × 16 Allen screws securing 2A20-407-2 to the end face of the thyratron housing 2A20-402-1A.

xii) Carefully withdraw 2A20-407-2. The CX1171A and its anode contact 2A20-411-4 will be withdrawn with it. Care must be exercised that the tube does not fall when 2A20-411-4 clears 2A20-553-3.

xiii) To remove the CX1171A unscrew the M6 fixing screws which attach it to 2A20-410-3. Remove the anode contact 2A20-411-4 by unscrewing its central retaining screw. Note that this screw must never be tightened -- its role is to prevent loss of 2A20-411-4 when withdrawing the tube. If tightened there is a risk of damaging the CX1171 when inserting the tube into its housing.

xiv) Remove the 2 × 270 Ω 3 W wire wound resistors from the gradient grid electrodes, retain for new tube.

3.5.3 Refitting of CX1171A

Refitting a CX1171A is basically a reversal of the foregoing operations. However, particular attention must be paid to the following points.

i) Before fitting 2A20-411-4 to the tube, check it is a good fit in 2A20-553-3. Always leave the fixing screw for 2A20-411-4 one turn loose in the CX1171A anode stud.

ii) Check the CX1171A carries its gradient grid resistors and the tapped lugs on anode, gradient grids and G2, and that these are tight.

iii) The correct rotational position must be respected when bolting the cathode of the CX1171A to 2A20-410-3.

iv) When introducing the CX1171A into its housing care must be taken to engage 2A20-411-4 in 2A20-553-3.

v) When refitting the tube tail wires in 2A20-412-2 this piece must be lowered to the lowest possible position inside 2A20-410-3 -- this prevents the multicontacts vibrating out downwards.

vi) Care must be exercised in simultaneously engaging all 5 M4 multicontacts of 2A20-440-2 with the 5 insulated columns. Correct engagement must be checked visually. Do not overtighten the nylon screws.

vii) When tightening the M10 × 80 bolts securing 2A20-443-3 and 2A20-426-3 the pieces must be held in such a manner as to prevent stressing the insulators of the LEMO sockets.

viii) The joint OR 81550 must be held in the groove of 2A20-414-3 with grease. Before refitting this cover carefully check that all coaxial and "multicontact" connections within 2A20-413-0 have been correctly made. Ensure that the ferrite ring on the G1 wire is in place. Do not overtighten the bolts securing 2A20-414-3 because 2A20-413-0 is annealed and has no helicoils. Secure the tube identification tag on one of the bolts.

ix) Refill with oil as detailed in MPS/AE/Note 74-2, page 15.

x) Do not uncap and refit the pulse transmission cables until the pulsing of all other modules has been stopped.

xi) Record all CX1171A movements in the "thyratron records file", noting normal and standby filament hours at the time of movement.

3.5.4 Removal and replacement of the SF_6/oil interface

i) Proceed as for CX1171A tube removal

ii) Empty PFN of SF_6 according to instructions of MPS/AE Note 74-1 Section 4.

iii) When PFN is at atmospheric pressure unbolt cable flange 2A20-406-2A from 2A20-404-2A and withdraw to disengage cable inner conductor past 2A20-404-2A.

iv) Unbolt 404-2A from 2A20-402-1A and withdraw the SF_6/oil interface complete.

v) Reassembly is a reversal of the preceding operations. Pay attention to fit a new indium contact wire in 2A20-404-2A and 2A20-406-2A.

3.5.5 Removal and replacement of the Faraday cage 2A20-445-1

i) Carry out the safety instructions of Section 3.5.1.

ii) Slacken eight of the retaining bolts of cover 2A20-417-1 and remove completely the remaining two bolts (centre top, centre bottom). It is not essential to remove the electrical cables supplying 2A20-417-1 but it is desirable. Remove 2A20-417-1.

iii) Unplug the multicontact connections in 2A20-408-2 -- these are size graded to prevent cross-connection.

iv) Unscrew the three special long hexagon nuts securing 2A20-445-1 to the steatite insulators -- use the special spanner provided. The Faraday cage is now free for removal.

v) Remounting is a reversal of the foregoing procedure. Pay attention to the correct engagement of 2A20-451-4 in the shaft of the reservoir heater potentiometer.

vi) If not previously calibrated, the reservoir heater voltage meter M2 must be controlled against the Gossen standard meter at 5.5 V. For this operation to be performed in the absence of HT the Faraday cage must be separately excited at 220 V r.m.s. 50 Hz. The M2 needle offset must be adjusted such that both Gossen and M2 meters simultaneously read 5.5 V with the Gossen connected to the reservoir heater tail wire (multicontact M4) at 2A20-408-2. Important -- the current drawn by the Gossen meter is considerable and it is therefore essential that the voltage calibration is made with both voltmeters simultaneously connected.

vii) If necessary the T2 transformer taps must be adjusted to obtain the desired reservoir heater voltage. (Maximum volts on 220 V tap, minimum volts on V3 tap.)

3.6 Routine maintenance

This can be divided into two parts; that which should be carried out with the equipment fully operational and that which must be carried out only after invoking the safety procedure of Section 3.5.1.

3.6.1 Equipment operational

i) Check pulse rise-time and compare with test report, check jitter with drift stabilizer in open and closed loop mode.

ii) Check trigger pulse waveform of pulse monitor output on trigger pulse amplifier and compare with test report.

iii) Check all thyratron protection systems for correct operation.

iv) Check and record heater, reservoir heater and grid 1 meter indications.

3.6.2 Equipment isolated

i) Check all Faraday cage connections, particularly heavy current connections on heater and reservoir heater transformer secondaries.

ii) With Faraday cage excited from separate 220 V a.c. source, check G1/cathode d.c. volt drop. For new tubes this is about 21 V. For ageing tubes up to 32 V. Record value.

iii) Check all screws of correct type are fitted to safety cover over Faraday cage.

iv) Clean air filter on underside of Faraday cage safety cover.

v) Check safety locking rings are in position on LEMO plugs.

vi) Replace lamp in Faraday cage (24 V, 3 W) after 1000 h of operation.

4. DUMP SWITCH

4.1 General

The purpose of the dump switch is to connect the 15 Ω PFN cable to ground via a matched terminator. The instant of triggering the dump switch with respect to the main switch determines the pulse length which appears in the magnet.

The dump switch forms a single mechanical assembly with the dump resistor and the HV part of the pulsed resonant power supply. This assembly is shown in 2A26-000-0A.

The electrical schematic of the dump switch is 2A32-928-2 and the "Faraday cage" schematic is 2A32-929-3.

4.2 Mechanical construction (2A26-000-0A refers)

The CX1171A thyratron is fixed by its cathode to the end flange 2A26-016-2 and is suspended vertically inside the housing 2A26-014-0. This housing is, in turn, bolted to the dump resistor housing 2A26-015-2A. The end of the PFN cable is connected to the base of 2A26-015-2A via flange 2A26-018-2. There is thus a coaxial assembly consisting of dump resistor and thyratron for the inner conductor and housings 2A26-014/015 for the outer conductor. Insulation between the HV components and the earthed housings is provided by a composite araldite/vetronite tube assembly 2A26-029-1 which is also suspended off the end flange 2A26-016-2.

Because the dump switch works with grounded cathode it does not require an isolated supply for its Faraday cage. However, a voltage divider for the 3 tube stages is needed and this is housed in tank 2A26-026-1 which communicates with housing 2A26-014-0 by an elongated hole running the full length of the CX1171A.

A number of the HV components of the pulsed resonant power supply are located in the circular tank 2A26-001-1. This tank is bolted to the resistor housing 2A26-015-2A in such a manner as to permit the passage of a tubular carbon mass resistor. This resistor serves to provide the electrical connection between PFN and power supply (it is in fact the filter resistor for the latter) and also to lead pressurized oil to the inside face of the dump resistor discs. Insulation of this filter resistor to ground is provided by the araldite/vetronite tube assembly 2A26-008-2. Whilst not part of the dump switch, brief mention will be made of the electrical components in tank 2A26-001-1. These are (a) the voltage divider used for PFN voltage measurement and power supply protection, (b) the 1 nF filter capacitor, (c) the diode stack, and (d) the HT bushing of the 20 kVA step-up transformer of the pulsed resonant power supply.

It should be noted that the power supply transformer, the power supply tank 2A26-001-1, the dump resistor and the dump switch are all mounted as a single assembly on base plate 2A26-005-1A. Lifting tackle exists for manoeuvring this single assembly.

The entire dump switch/pulsed resonant power supply assembly is oil filled. The high-voltage transformer is filled with static oil, the transformer having its own silica gel breather and conservator. The rest of the assembly is filled with oil which is circulated by the main oil pump (see MPS/AE/Note 74-2). The feed-in point is on the side of tank 2A26-001-1, but the oil is immediately led by a pressure tight pipe and the hollow tubular charging resistor to the inside of the dump resistor. From here the oil escapes to the outside of the dump resistor via the porous metal discs fitted between each resistor disc. This oil then rises between the inner and outer conductors of the coaxial system and passes over the CX1171 thyratron, the hot oil finally leaving the assembly via an outlet at the highest point of the end flange 2A26-016-2. To assist in filling tank 2A26-001-1 a valved connection is provided between its cover 2A26-002-2A and the end flange 2A26-016-2. Other than when filling, this valve (designated V_F in instructions MPS/AE/Note 74-2) must remain closed. The normal oil flow is approximately 3 ℓ/min. After circulation in the dump switch assembly the oil is fed to the associated main switch assembly via cover 2A20-429-2 as described in Section 3.2. The dump switch assembly therefore has to withstand the sum of the pressure drops of both the main and dump switches. At 3 ℓ/min this pressure drop is normally 0.8 kg/cm^2 measured at tank 2A26-026-1; a safety valve is fitted which opens at 1.1 kg/cm^2.

Connections between the CX1171A tube and the tube voltage divider assembly 2A26-037-2 are made by insulated flexible columns 2A26-035-4. Note the use of two different column lengths, a long column (130 mm) for the anode and short columns (125 mm) for the two gradient grids. The externally-mounted Faraday cage metal work is at earth potential and natural air cooling is employed. Connections from Faraday cage to CX1171 base are made via flying leads and the araldite insulator 2A26-017-2; bolted connections are used on the outside and "multicontacts" on the inside.

4.3 Electrical circuit (2A32-928-2 refers)

The dump resistor and the anode end of the CX1171A tube are insulated to withstand the 80 kV pulsed low-frequency resonant charging voltage. The cathode of the CX1171A being grounded, the grid and auxiliary supply circuits are only lightly insulated. It is therefore important that the dump switch cathode is always solidly grounded.

The connection point of the pulsed resonant power supply between CX1171A anode and dump resistor has been chosen so as to minimize the disturbance to the magnet pulse form due to power supply capacitance. All the stored energy on the HV side of the power supply is discharged when the CX1171A dump switch conducts.

The PFN cable is charged via a HV diode stack (Unitrode UDA 10 modules rated for 200 kV). These diodes are protected against the fast switching surge of the CX1171A by a 2.5 k Ω Carborundum rod resistor and a 1 nF 100 kV capacitor. Measurement of the PFN voltage is made at a point between the HV diode stack and the 2.5 k Ω resistor. This measurement is strobed at an instant when the 2.5 k Ω resistor current is zero so that the value obtained is the true PFN voltage. The HV measurement divider is equipped with two outlets, calibrated 1 V and 10 V per 100 kV, respectively. These are used for (a) power supply monitoring and (b) digital voltage display with feedback to the step-by-step servo, together with overvoltage protection.

The dump resistor is a spring-loaded column of carbon mass resistor discs with interspersed porous metal washers. Its value must be closely adjusted to the cable Z_0 (i.e. 15.00 Ω) by disc selection.

The CX1171A tube voltage divider follows closely that used on the main switch and the same remarks concerning rating apply. Gradient grid resistors are located on the dump thyratron as for the main thyratron.

Two monitoring devices are provided on the dump switch assembly to check the switching action. The first is a 3-turn coil fixed to flange 2A26-016-2; the signal of this coil is proportional to the switched dI/dt. This signal is integrated and used for the dump thyratron protection. The second is a capacitive pick-up located on the PFN cable flange 2A26-018-2. This signal is taken to the fast monitoring system where it is integrated and can be displayed, by appropriate selection, on the fast monitoring scope. The signal displayed exhibits two negative steps, their separation depending on main and dump switch timing. The first step allows the switching performance of the dump to be checked (the second step is an indication of the switching performance of the main deteriorated by the PFN attenuation). Alternatively, the switching action of the dump can always be assessed by looking at the fall of the main terminator pulse, but in this case both PFN and transmission cable attenuation effects must be taken into account.

The G2 bias and trigger pulse are applied through a simple filter consisting of two resistors and a capacitor mounted on flange 2A26-016-2.

The dump switch Faraday cage (2A32-929-3) is directly mounted on the earthed dump switch housing. It has a similar circuit to that of the main switch excepting that (a) the G1 interlock is closed via a relay RL1 directly in the G1 circuit, (b) the cage also contains the thyratron trigger pulse transformer T4 and (c) the transformer T1 is of a different type with a secondary voltage of 55 V r.m.s. (This is because the open-circuit G1 voltage requirement is higher for the main than dump). The dump switch Faraday cage is supplied in parallel with the main switch cage from the same Philips stabilizer. Monitoring of the dump switch heater, reservoir and G1 supplies is similar to that described for the main.

4.4 Protection

The dump switch is protected against overheating by an oil flow relay which trips the HV power supply if the oil flow falls below about half its normal rate of 3 ℓ/min. There is no oil temperature protection other than that for the entire oil-cooling system at the pump.

The electrical protection which is provided is as follows:

i) Warm-up time interlock.
ii) Grid 1 current interlock.
iii) Faulty shot (or spontaneous breakdown) interlock.
iv) Drift stabilizer interlock.

The manner of the operation of this protection is similar to that already described in Section 3.4 for the main switch, but using the sensors outlined in Section 4.3.

4.5 Dismantling and rebuilding instructions

4.5.1 Safety

The safety instructions of Section 3.5.1 must be observed in their entirety. The dangers are the same when working on dump or main switches.

4.5.2 Removal of CX1171A

i) Drain the switch oil by opening the by-pass valve V_{BP}, closing the inlet and outlet valves V_I and V_O, and opening the drain valve DV (refer to colour code for valve identification). Open vacuum valve VV and allow switch to drain into drain tank until the level has fallen below the bottom of the voltage divider tank 2A26-026-1. Close DV to prevent further draining. Attach a short length of flexible pipe to the small drain valve fitted to the base of 2A26-026-1 and drain the small residual oil volume of this tank.

ii) Remove voltage divider tank 2A26-026-1 thus exposing the CX1171A voltage divider.

iii) Remove perspex cover 2A26-032-4. Unscrew the 4 nylon screws retaining the voltage divider platform 2A26-036-3 to the perspex insulation 2A26-028-1. Unscrew the divider tail wire (M4) where it is joined to housing 2A26-014-0. Remove the voltage divider 2A26-037-2.

iv) Unscrew and retain in original order the insulated columns 2A26-035-4. (Note the anode column is 5 mm longer than the two gradient grid columns).

v) Remove the perspex cover 2A26-042-4 and unscrew the 3 Faraday cage tail wires from the lead-through 2A26-017-2. Detach the RG 59 cables from the "coil" and "trigger" BNC's fitted in flange 2A26-016-2.

vi) Remove the fixing bolts attaching 2A26-017-2 to 2A26-016-2. Withdraw 2A26-017-2 and detach the tube tail wires (multicontacts) from the interior.

vii) Remove the fixing bolts holding 2A26-016-2 to the thyratron housing 2A26-014-0. Carefully withdraw the CX1171A still attached to flange 2A26-016-2.

viii) To remove the CX1171A tube, disconnect the G2 connection and unscrew the three M6 fixing screws which attach it to 2A26-016-2. Remove the anode connection piece 2A26-021-3A by unscrewing its central retaining screw. Note that this screw must never be tightened fully -- its role is to prevent loss of 2A26-021-3A when withdrawing the tube.

ix) Remove the gradient grid resistors (2 × 270 Ω 3 W wire wound), retain for new tube.

4.5.3 Refitting of CX1171A

Refitting is a reversal of the dismantling procedure of Section 4.5.2. Particular care should be taken on the following points:

i) Check 2A26-021-3A makes good contact in 2A26-025-3 before refitting to the tube. When refitting leave the centre fixing screw one turn loose.

ii) Check that the CX1171A carries its gradient grid resistors and the tapped lugs on anode, gradient grids and G2, and that these are tight.

iii) The correct rotational position must be respected when bolting the CX1171A to 2A26-016-2.

iv) The tube tail wires must be refitted into the multicontact sockets of 2A26-017-2 before fitting the latter to 2A26-016-2.

v) When refitting the tube voltage divider 2A26-037-2, make sure that all flexible columns 2A26-035-4 are engaged in the multicontact sockets. Do not overtighten the nylon screws holding 2A26-037-2 to 2A26-028-1.

vi) Refill with oil as detailed in MPS/AE/Note 74-2, pages 13-15.

vii) Record all CX1171A movements in the "thyratron records file", noting normal and standby filament hours at the time of movement.

4.5.4 Removal and replacement of dump resistor

Proceed as in Section 4.5.2 for the removal of the CX1171A and then continue as follows

i) Drain more oil from the system so that the level is about half-way down the power supply diode tank 2A26-001-1.

ii) Remove cover 2A26-002-2A and disconnect the HT connection from 2A26-010-4A.

iii) Remove Carborundum carbon mass resistor by unbolting flange 2A26-004-4 from 2A26-001-1 (after firstly removing the external oil pipe) and removing the bracket which attaches the resistor to the top of the voltage measuring divider. The resistor together with plastic tube and 2A26-004-4 can then be withdrawn sufficiently to clear it from engagement with 2A26-030-2. (Note that an O-ring oil seal and spring electrical contact are contained in 2A26-030-2; these are not disturbed by removal of the resistor and, in principle, reassembly is a simple reversal of removal).

iv) Remove the 4 Allen screws which retain the vetronite cylinder insulation 2A26-008-2. Withdraw this insulation from the grooves in the main coaxial insulation 2A26-029-1. It is not necessary to remove 2A26-008-2 completely; it may be left on the top of the voltage divider assembly 2A20-900-3 in order to avoid removing the large vetronite cylinders 2A26-012-2A.

v) Unbolt the thyratron housing 2A26-014-0 from the resistor housing 2A26-015-2A. Note the use of a Ø 1 mm indium wire contact between these two parts which must be renewed on reassembly.

vi) Remove the 4 bolts securing ring 2A26-039-3 to the vetronite insulation assembly 2A26-029-1 and the 6 bolts securing 2A26-039-3 to 2A26-014-0. Lift off 2A26-039-3.

vii) Lift off the thyratron housing 2A26-014-0.

viii) Lift out the vetronite insulation assembly 2A26-029-1, making note of its orientation for reassembly.

ix) Remove the bolts securing the anode connector 2A26-025-3 to the resistor end plate 2A26-030-2. Note the O-ring fitted between these components which must be replaced on reassembly.

x) Fix suitable lifting tackle to the M16 thread provided in the compression spring adjuster 2A26-020-4 and lift out the resistor assembly.

xi) Before dismantling the resistor assembly, measure on a reference table the height of the location of the Carborundum carbon mass resistor in 2A26-030-2 with respect to the M10 bolt head screwed into the lower end plate 2A26-024-2. This height must be re-established on reassembly, either by selective assembly or by adjusting the M10 head thickness. Failure to follow this instruction will result in difficulties in remounting 2A26-008-2 and can lead to HV breakdown. Because of fairly large tolerances in the glueing of the SF_6/oil interfaces this height varies from switch to switch and, in consequence, the dump resistors are not necessarily freely interchangeable.

xii) Reassembly is basically a reversal of the foregoing. In addition to the points already mentioned it is important when rebuilding the dump resistor that the discs used are already fully oil impregnated that they are flat and that the assembly is spring-loaded to approximately 340 kg, i.e. 18-19 mm spring compression. Check after loading that the resistor stack is straight and the discs uncracked.

Refitting of the CX1171A should be carried out according to Section 4.5.3.

4.6 Routine maintenance

This can be divided into two parts; that which should be carried out with the equipment fully operational and that which must be carried out only after invoking the safety procedure of Section 3.5.1.

4.6.1 Equipment operational

i) Check CX1171A switching action by observation (a) of magnet terminator pulse fall-time and (b) integrated signal from capacitive pickup at dump resistor. Check jitter with drift stabilizer in the open and closed loop modes.

ii) Check trigger pulse waveform and compare with test report.

iii) Check all thyratron protection systems for correct operation.

iv) Check and record heater, reservoir heater and grid 1 indications.

v) With pulsing suppressed, measure and record the G1/cathode d.c. volt drop. For new tubes this is about 21 V and for ageing tubes up to 32 V.

4.6.2 Equipment isolated

i) Check all Faraday cage connections, particularly heavy current connections of heater and reservoir heater transformer secondaries.

ii) Periodically check resistance values of dump resistor, voltage measuring divider, tube voltage divider and power supply filter resistor. Record and compare with test report values. If necessary readjust dump resistor (by disc replacement) to maintain a close match with PFN impedance and magnet terminator (nominal value 15.00 Ω). (Note: The dump resistor can be measured between the main and dump switch anodes without invoking the removal procedure of Section 4.5.4. In this case 19 mΩ should be deducted for the PFN inner conductor resistance).

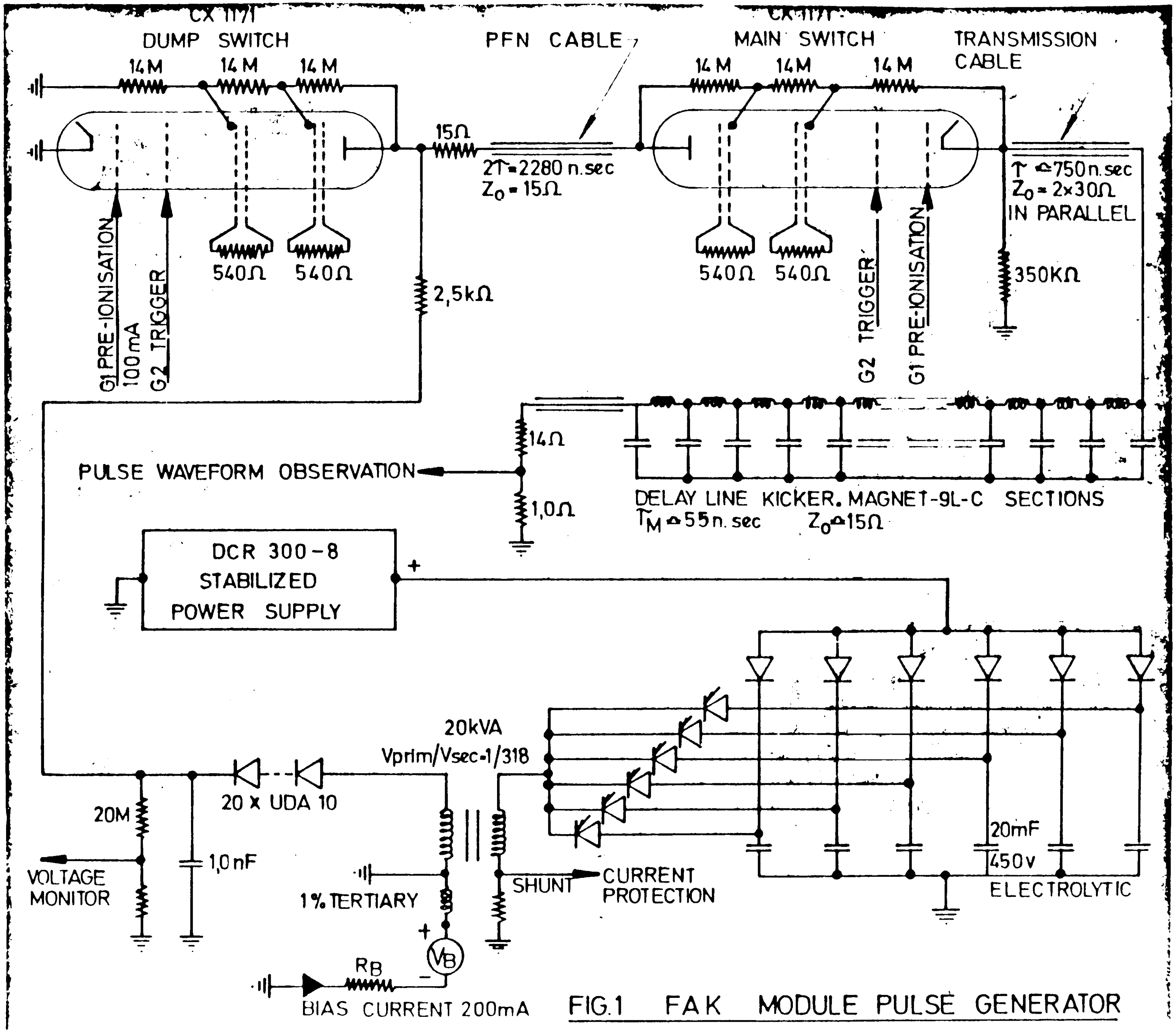

FIG.1 FAK MODULE PULSE GENERATOR