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A PULSE GENERATOR FOR SHORT-CIRCUITED DELAY LINE MAGNET EXCITATION

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Summary

CERN is adding a new Antiproton Collecting (AC) ring to its existing Antiproton Accumulator (AA) to increase the particle collection rate. The bunched 3.5 GeV/c beam from the target station is injected every 2.4 s into AC and shortly afterwards transferred to AA. This requires fast pulsed delay line kicker magnets. Shortage of space in the rings imposes short-circuited rather than matched magnets, the requisite deflection then being obtained at acceptable Pulse Forming Network (PFN) voltage (80 kV).

The special pulse generators for excitation of the short-circuited magnets are described. One feature is double-ended switching of the 15 Ω cable PFN, permitting magnet pulse length variation (100-2000 ns). A more novel feature is the use of a hollow anode thyratron as a bi-directional switch operating with inverse to forward charge ratios of up to 20:1. Detailed performance of two types of hollow anode thyratron, one conventional and one with additional anode gradient grid, are examined with particular reference to the inverse switching characteristics. The satisfactory outcome of extended life testing is reported.

Introduction

The CERN antiproton production facility was commissioned in 1980 and has since made a unique contribution to particle physics research. Antiprotons produced at a target station by 26 GeV/c protons impinging on a copper target are collected and transported to the AA where they are injected using fast delay-line kicker magnets. This process of antiproton production and injection is repeated every 2.4 s, and continues concurrently with stochastic cooling of those antiprotons already injected into the AA. After a stacking period of up to 24 h a fraction of the cooled 3.5 GeV/c beam is extracted, again with a fast kicker magnet, and transferred via the 26 GeV/c proton synchrotron to the large hadron collider (SPS). The facility operates continuously during long physics experiments and must be highly reliable.

The growing need of experimenters for more antiprotons has resulted in an improvement project for the facility. In addition to an improved target station, a new AC ring is to be placed around the AA, with a transfer line linking the two rings. The AC has increased momentum and transverse acceptances with respect to the AA, such that an order of magnitude increase in antiproton availability for experiments should be obtained.

In the future, antiprotons produced at the target station are to be injected into the AC and, after precooling, transferred to the AA; both the injection and ejection processes use delay line kicker magnets. Because of shortage of suitable space on the AC periphery its kicker magnets have to be short-circuited to furnish the required bending strength at acceptable PFN voltage and impedance levels. Accumulation and stack cooling will continue to take place in the AA, a new influx of antiprotons arriving every 2.4 s from the AC. No changes are needed to the existing AA ejection system.

The improvement project calls for considerable investment in kicker magnet and pulse generator hardware for the two new systems needed for the AC and the totally rebuilt injection system needed for the AA. The installation programme, which allows only six months between the shutdown of the existing facility and the start of beam trials in the new one, adds a constraint which encourages the maximum re-utilisation of existing equipment.

This paper describes development work aimed at modifying the ten 80 kV, 100 MW pulse generators of the present terminated delay-line magnets to make them suitable for driving short-circuited delay-line magnets. The objective has been to find solutions which would involve the least possible alteration to high voltage hardware. Most effort has been devoted to investigating the ability of socket compatible hollow anode thyratrons to handle the large inverse current reflected by the short-circuited magnets. Clearly conversion of the existing pulse generators for short-circuit load operation by a simple tube change would have important cost and time advantages.

Existing pulse generators for terminated magnets

The architecture of one of the existing generators is shown in Fig. 1, together with the wave pattern and currents resulting from triggering the two CX 1171 thyratrons T1, T2. Pulse length control is by adjustment of the trigger delay between T1 and T2. The rising edge of the load pulse is determined by the switching performance of T1 and the falling edge by T2. Both thyratrons pass only positive current, even in the event of self firing. Short-circuiting of the load, as in the case of magnet breakdown, results in some inverse current in T2 but which can be supported by the CX1171 provided protective devices stop PFN recharging immediately. The operating PFN voltage is 80 kV. Switching at > 100 A/ns is obtained with jitter < 5 ns and each generator has operated satisfactorily for 50 million pulses.

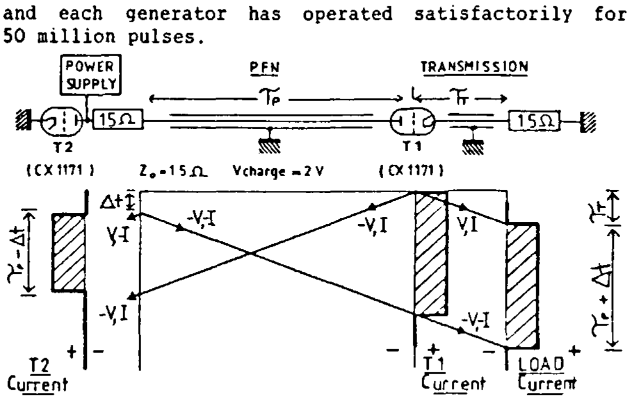

Fig. 1. Existing pulse generator with wave diagram.

Proposed pulse generators for short-circuited magnets

Fig. 2 shows the proposed generator and its wave pattern. Thyratron T1 now has to handle twice the previous current for a duration dependent on the thyratron trigger delay Δt and the PFN and transmission cable delays. Thyratron T2 has to handle bi-polar current, the current blocks being separated by twice the transmission delay. Switching delay or thyratron housing impedance mis-match can give rise to undesirable reflections in the short-circuited load current, which would disturb beam transfers. Of the five principal reflections shown in Fig. 2 the first and second arise from the inability of T1 to fully transmit the waves returned from the short circuit. The other reflections are due to deficiencies of the bi-directional T2. The fourth reflection is of particular interest as it is a sensitive indication of the inverse switching performance of T2.

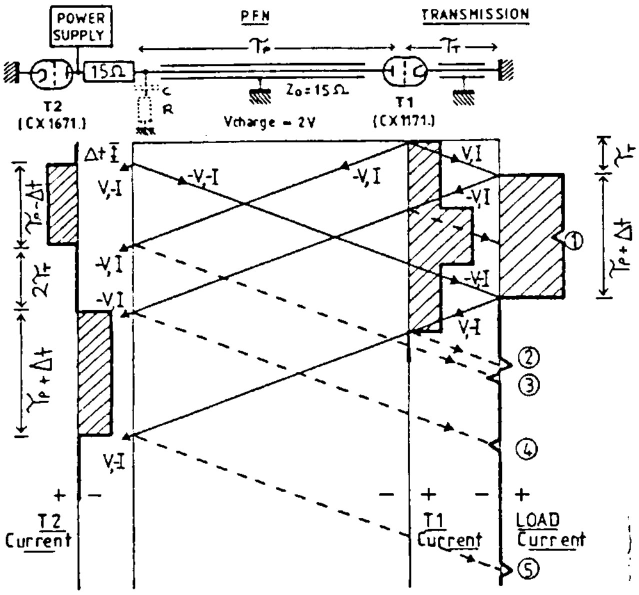

Fig. 2. Proposed pulse generator with wave diagram.

Two solutions were considered to provide a bi-directional T2 switch. The first, and certain, solution would have been to use the double cathode CX 1171B but this would have involved rebuilding large quantities of high voltage hardware and was dropped in favour of trying the socket compatible hollow anode version of the CX 1171, the CX 1671A. Hollow anode thyratrons had been developed to cope with the inverse current in excimer laser circuits but their use in circuits where reverse charge far exceeds forward charge would be breaking new ground. The principal interest of the development programme, therefore, was centred on the switching and inverse conduction characteristics of the hollow anode thyratron.

The CX 1671A switching characteristics

The CX 1671A switching characteristics in the T2 location have been deduced from observation of its anode current and voltage waveforms, with confirmation from the observed reflections in the short-circuit load current. These characteristics have been investigated as functions of PFN voltage, transmission cable delay and forward to inverse charge ratio. Typical T2 and short-circuit current waveforms are shown in Fig. 3.

The initial turn-on performance is sensibly that of a CX 1171; at 80 kV PFN voltage the 10 - 90% rise time is faster than 30 ns with maximum di/dt of 125 A/ns and jitter below 5 ns. The anode current and voltage wave-forms during commutation (Figs. 4a and 4b) provide useful information to evaluate the tube inductance and inverse switching voltage; from the positive current fall the inductance of the CX 1671A in its housing is 85 nH. The inductance is also independent of the forward conduction period and is confirmed from the negative current fall. The negative current rise is clearly subject to some delay because the anode voltage builds up to more than 17 kV, a level about three times that which can be attributed to the tube inductive drop alone, indicating that the inverse switching voltage is in excess of 10 kV. The anode voltage during commutation (Fig. 5) shows that whilst the inductive drop is proportional to PFN voltage the voltage at inverse switching is not, and tends to confirm a minimum switching voltage of 10 kV irrespective of PFN voltage. There is also a period of 200 - 300 ns after the establishment of inverse current when the tube has high internal resistance, the anode voltage dropping slowly from about 3 kV to zero. The

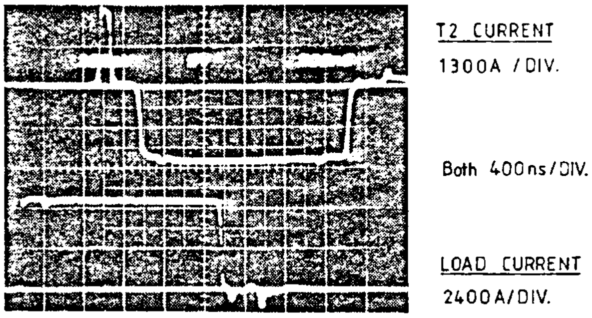

Fig. 3. Typical T2 and short-circuit current waveforms.

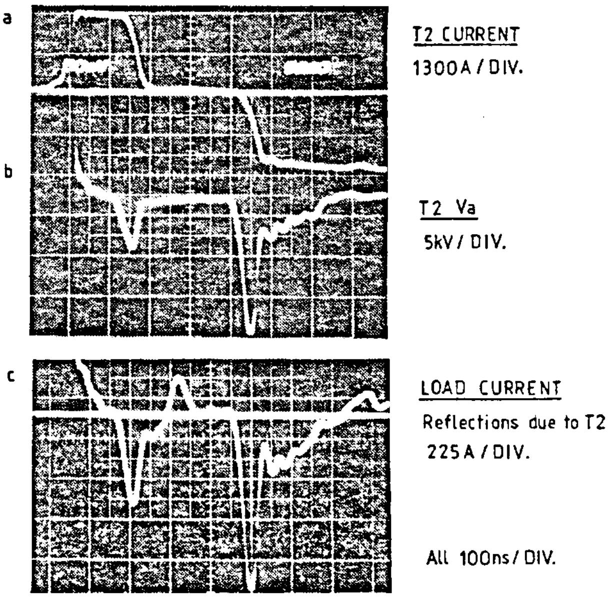

Fig. 4. T2 commutation and resulting reflections.

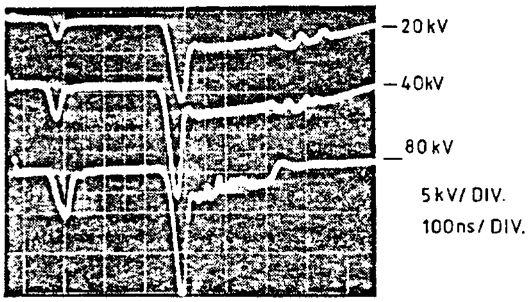

Fig. 5. V_A versus V_{PFN} during commutation.

consequence of the finite tube inductance and the inverse switching delay is to cause unwanted reflections in the load current (Fig. 4c) of similar form to the anode voltage waveforms of T2.

In an effort to localise, and if possible reduce or eliminate the inverse switching delay, measurements were made (at reduced PFN voltage for convenience) of the voltage division across the tube gaps (Fig. 6). It

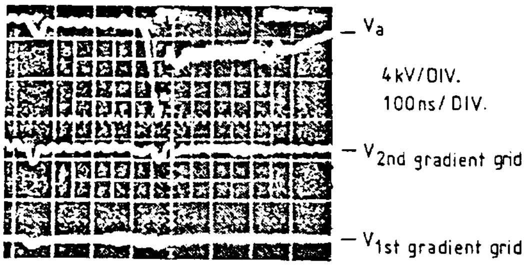

Fig. 6. Voltage distribution across T2 at commutation

is seen that whilst the inductive drop at current fall is reasonably shared between the three gaps, the voltage build-up at inverse switching is held entirely across the anode gap. Any improvement in the inverse switching therefore requires that the anode gap be more readily conducting when the negative current wave arrives. Changes in the transmission cable length, resulting in changes in the time between forward and inverse conduction in the range 75 - 400 ns, had almost no effect on the inverse switching. Changes of the forward/inverse charge ratio of 1 : 20 through to 20 : 1 made some improvement, the anode voltage build-up being somewhat lower after a long period of forward conduction.

Computer modelling had shown that an R-C filter placed at the T2 end of the PFN would be able to suppress T2 induced reflections in the short-circuit provided they were of both similar shape and duration. The disparity of the reflections (Fig. 4c) precludes full suppression.

Attempts to improve the inverse switching by connecting R-C networks across different gaps of the tube in turn had the object of maintaining the top gap in forward conduction during the commutation delay or driving into inversion conduction before the arrival of the inverse current wave. Whilst it was possible to maintain forward conduction, this brought no improvement to the inverse switching. Driving the top gap into early inverse conduction was impossible, the desired inverse current being preferentially conducted as forward current in the two lower gaps and shunted through the load short-circuit and T1 back to the anode of T2.

Notwithstanding the minor inverse switching deficiencies of the CX 1671A it has been very successfully life tested in a prototype pulse generator, where it has operated at 80 kV for 30 million pulses switching a forward current pulse of 200 ns and inverse pulse of 1800 ns. Its switching performance at the end of the test showed no deterioration.

<u>An improved CX 1671A - the version 'X'</u>

Improved T2 inverse switching should be possible if recovery of its anode gap can be retarded. To this end the anode region has been redesigned to incorporate an anode gradient grid with substantial drift space between it and the anode (Fig. 7). This modified CX 1671A - the version 'X' - has been tested in the T2 location, showing turn-on time, voltage hold-off characteristics and inductance similar to a standard

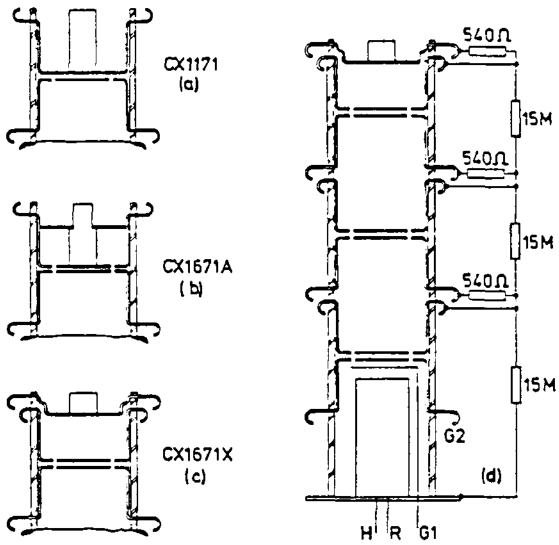

Fig. 7. Potential divider and schematic of anode construction

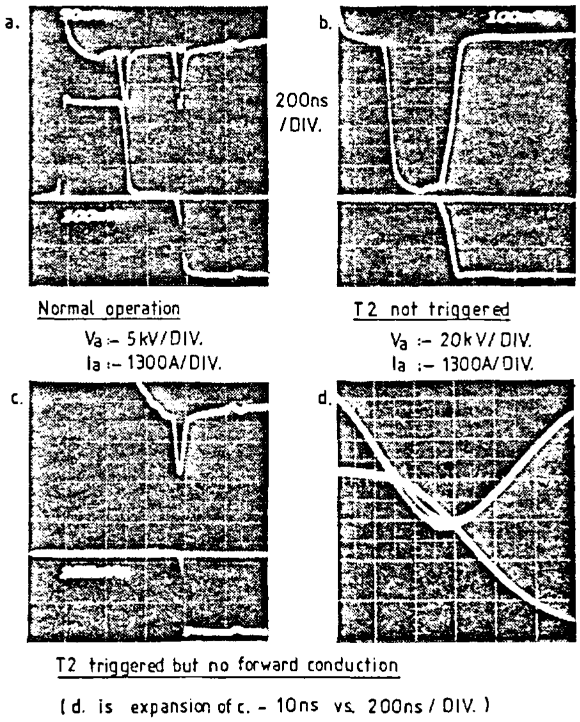

Fig. 8. Inverse conduction of T2 with and without forward conduction.

CX 1671A. However the inverse switching characteristic, Fig. 8a, is markedly improved, the anode voltage spike at the negative turn-on being little bigger than that of the positive turn-off. The previous high tube resistance in the initial 300 ns of inverse conduction has also disappeared. This excellent inverse switching is confirmed even with all forward current suppressed (Figs. 8c, 8d) provided that the tube is triggered. Without triggering, the full 80 kV voltage builds-up across the tube before inverse sparking, delayed by 300 ns, takes place (Fig. 8b).

Fig. 9 shows the significantly lower anode voltage at inverse switching of the 'X' version. After deduction of the inductive drop (Fig. 10) the 'X'

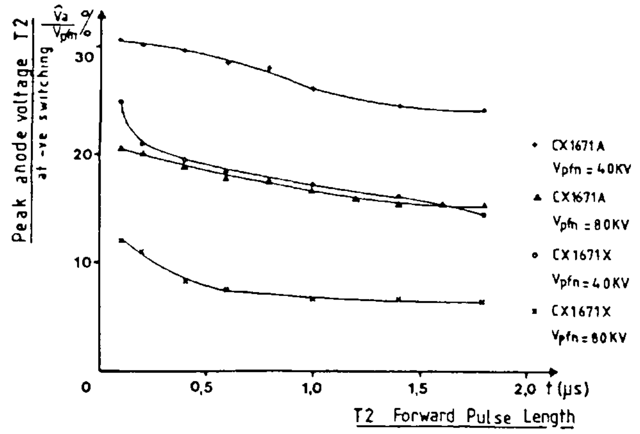

Fig. 9.

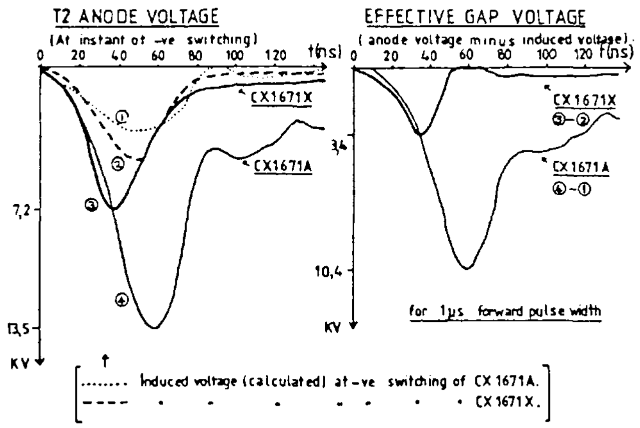

Fig. 10

switching voltage is only 3.4 kV against more than 10 kV for the standard tube. Inverse switching has been investigated over the range of PFN voltage of 40 to 80 kV and forward pulse lengths of 200 to 1800 ns. Most stable switching, with minimum anode voltage spike and jitter, is obtained at high PFN voltage and long forward current pulse, with the influence of voltage level the more predominant. Ten overlayed shots of anode voltage and inverse current rise for the extremes investigated are shown in Fig. 11.

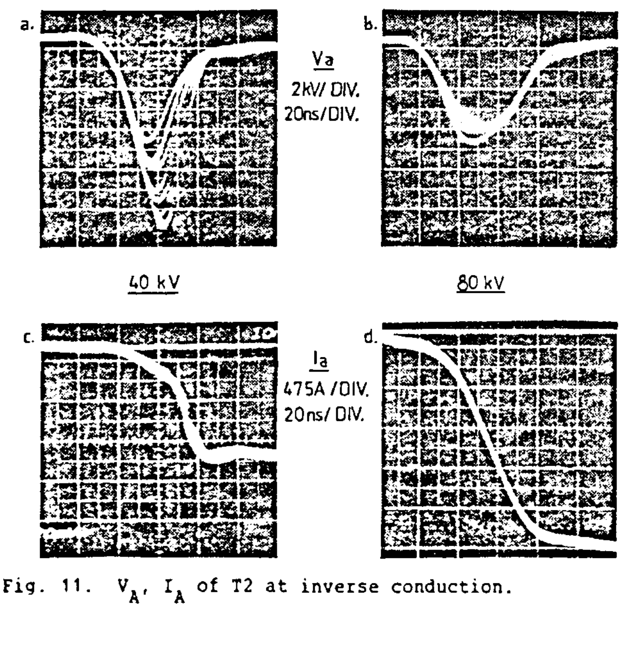

Fig. 11. V_A, I_A of T2 at inverse conduction.

The resulting short-circuit load current with the CX 1671X in the T2 location is shown in Fig. 12a, with an expansion (Fig. 12b) of the T2 induced reflections. Figs. 12c and 12d confirm the beneficial effect of adding a 520 pF, 15 Ω filter at T2. The small mismatch and spike on the flat top of Fig. 12c arise from an easily removable defect of the test generator; with this corrected the quality of the excitation pulse for the short-circuited delay-line kicker magnets will be excellent.

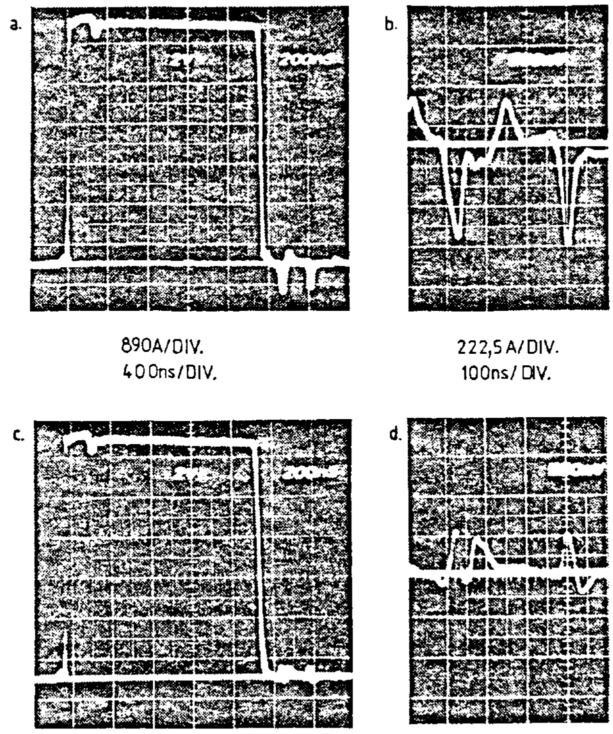

Fig. 12. Short-circuit current without and with filter at T2.

Conclusions

It has been shown that the standard CX 1671A hollow anode thyratron is able to switch and sustain inverse currents of 2.6 kA for up to 2 μs even when the forward charge is but a very small fraction of the inverse charge to be handled. There is some switching delay as the tube goes into the inverse mode, the anode gap voltage rising to about 10 kV, followed by a resistive voltage drop of a few kV in the initial 300 ns of inverse conduction. A development of the CX 1671A, the CX 1671X, having an additional anode gradient grid, shows markedly improved inverse switching with minimal delay and very low internal impedance to reverse current, whilst still retaining all the positive characteristics of the CX 1671A.

The CX 1671A has been life tested for 30 million pulses and the CX 1671X for 4 million pulses (still continuing), sufficient to justify a firm decision to implement the conversion of the pulse generators for short-circuit duty with one or other of these hollow anode tubes.

Acknowledgements

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