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100kV, 80A, 10s POWER SUPPLY FOR A NEUTRAL BEAM INJECTOR USING A SERIES OF GATE TURN OFF THYRISTORS AS A REGULATOR SWITCH VALVE

June 1984

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100kV, 80A, 10s Power Supply for a Neutral Beam Injector Using a Series of Gate Turn Off Thyristors as a Regulator/Switch Valve

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A voltage regulated GTO valve was devised and applied in the accel power supply of the prototype injector unit for JT-60 with particular intension to check its applicability to the JT-60 NBI power supplies. High reliability and applicability were confirmed by performance tests. Based upon test results, we decided to use GTO valves in accel power supplies for JT-60 NBI.

Keywords : Neutral Beam Injector, Accel Power Supply, Regulator, Switch Tube, Gate Turn off Thyristor, JT-60, Performance Tests

* On leave from Toshiba Corporation

レギュレータ／スイッチバルブとしてゲートターンオフサイリスタを用いた中性粒子入射装置用100kV, 80A, 10秒電源

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（1984年5月29日受理）

電圧制御機構を有するGTO（ゲートターンオフサイリスタ）バルブを考案し，JT－60 NBI原型ユニットに適用した。これは，特にJT－60 NBIへの適用性を調べるために行われたものである。性能試験により本GTOバルブは，高い信頼性と適用性を有することが確認できた。この結果からJT－60 NBI用加速電源にも本GTOバルブを用いることとした。

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1. Introduction

In JT-60, 20 MW hydrogen neutral beams will be injected in order to achieve reactor-grade plasmas and to investigate physical and technological aspects relevant to fusion reactor development.[1] The Neutral Beam Injection system for JT-60 is composed of 14 injector units; each is designed to deliver a 1.43 MW neutral beam with an energy of 75-100 keV for 10 sec using two ion sources.[2] Prior to fabrication of the 14 injector units, a prototype injector unit was constructed at the end of 1981 to test the injector unit performance. This unit succeeded in injecting the rated neutral power into the target chamber, which simulates the JT-60 vacuum vessel, over energy range mentioned above.[3)-7)] It was confirmed that all components, including the power supply system worked successfully.

The power supply and control systems for the ion sources in the NBI unit are generally the most crucial factor in achieving reliable beam extraction. The basic features of the power supply system for the prototype unit have been reported elsewhere.[8] After its completion, several improvements have been made on the power supply system. The most drastic change is the replacement of the high power vacuum tube, which functions as a regulator/switch valve in the accel power supply, with a series of gate turn off thyristors (GTO). This was initiated because several disadvantages were found with the tube in the prototype unit, one of which is internal parasitic oscillation. This problem can nearly be eliminated by structural modification of the tube itself, the use of oscillation suppressor elements, and the selection of tube operational region. Even after these countermeasures, however, the oscillation occurs occasionally and seems to be impossible to suppress completely. The second disadvantage is that flashovers occur in the tube occasionally. They occur even during operation at very low voltages, compared with tube catalog value, in the initial stage of use. Flashovers become less frequent as the tube is conditioned and the operating voltage can be increased gradually. But it seems impossible to eliminate the crowbar switch, which protects the tube at flashover. The use of a crowbar switch makes a system more complex and less reliable. The third disadvantage with the tube, which may be the largest for future injectors, is large anode dissipation. This makes system efficiency low. All these problems seem to be solved if the tube is replaced by a properly designed GTO valve.

A GTO valve was first adopted as a switch valve in an accel power supply at the test stand of Nagoya Univ.[9] Hitachi Co. Ltd. has also built a similar valve with a slavefire circuit by its internal effort.[10] When a series of GTO is adopted as a valve, the biggest disadvantage is that GTO elements themselves are lack of voltage regulation. In particular, input valtage of a GTO valve just after breakdown becomes higher than its set voltage, which in turn produces overshoot during the beam recovery phase and induces unnecessary breakdowns. To solve this problem we devised a voltage regulated GTO valve. GTO characteristics such as turn off time may cause unique problems when adopted in an accel power supply. To examine the applicability of a voltage regulated GTO valve to the accel power supply of NBI with particular intension to apply to the JT-60 NBI, the regulator/switch tube in the accel power supply of the prototype unit was replaced by a voltage regulated GTO valve in Dec. 1983. Performance tests of the GTO valve continued until mid Feb. 1984. This system demonstrated stable operation and no essential disadvantage appears to exist in comparison with the tube.

In the present paper, we report the experimental results of this performance test in detail. In §2, the system outline of the prototype unit is described. The experimental results are described in detail in §3 and we conclude the applicability of regulated GTO valves in accel power supplies of NBI systems in §4.

2. System Description

The overall description of the prototype unit can be found elsewhere.[11] Figure 1 and Table I are the schematic diagram and the fundamental specifications of the power supply system, respectively. In the following subsections, the accel power supply, the plasma generator and suppressor grid power supplies, the time sequence, and the ion sources are described.

2.1 The accel power supply

In order to supply gradient grid voltage, a tube-resistor divider was selected because it affords to feed the high current required in the beam initiation phase and thus is capable of voltage control even if the tube is replaced by a properly designed GTO valve.

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2.1 The accel power supply

In order to supply gradient grid voltage, a tube-resistor divider was selected because it affords to feed the high current required in the beam initiation phase and thus is capable of voltage control even during perveance mismatched beam initiation from the underdense side. The beam initiation from the underdense side makes laborious adjustments of timing or waveforms unnecessary and, as a result, permits the use of a GTO valve. Furthermore, the tube-resistor divider also has the ability to change the ratio, Γ, of gradient grid voltage to accel (plasma grid) voltage during the pulse.[7)]

The GTO valve is composed of GTAS and GTAR. A 100 series element GTO stack (GTAS) is dedicated to switch on and off the DC current only, while a 20 series element stack, each provided with a parallel non-linear resistor (GTAR) serves the role of holding the overcharged voltage and each GTO independently becomes conducting as the voltage decreases when the beam initiates. The limiting voltage of each non-linear resistor used in GTAR is about 1kV. The specifications of the GTO's used are listed in Table 2. The voltage safety factor based on the maximum rated voltage of 100 kV is 2.5. The regulator/switch tube has been replaced by a set of the GTO valve and a L-R-Diode element connected to the output side of the GTO valve (see Fig. 1), while a crowbar switch to protect the tube was eliminated. The function of the L-R-Diode element is to limit the surge current during source breakdowns. The accel voltage is roughly set by a transformer with tap-changer. Fine control of the accel voltage is made by phase-control of the AC thyristor switch, QSWA, which has a hybrid feedback loop of both the DC output voltage and the DC output current to achieve fast regulation.

In NBI power supply system, stray capacitance and its countermeasure have a definite role of the performance. In the prototype unit, the accel voltage is supplied to the plasma grids through an air insulated cable duct with the electrical power to the plasma generator. The gradient grid voltage is fed through a coaxial cable whose outer conductor is connected to the accel voltage. In this system, stray capacitance can be grouped into two sets. One, which is charged up to the accel voltage, is the sum of the stray capacitance in the isolation transformer of the plasma generators and the distributed capacitance of the cable duct. This is estimated to be as much as 24000 pF. The other, which is charged up to the accel voltage minus the gradient grid voltage, is distributed in the gradient grid's coaxial cable, and is about 7000 pF. A ferrite core of 30 μH, ±0.02 Vs with a resistor of 12.5 Ω in the secondary winding is present for surge protection. Although the original function of the diode D1 is to suppress the back swing of the accel voltage after source breakdown, the resistor located at the anode of the diode also absorbs the surge energy.[12] It should be noted that stray capacitance affects the initiation characteristics of the accel and gradient grid voltages.

2.2 The power supplies for the plasma generators and the suppressor grids

A 5 parallel element GTO stack is also used in each arc power supply. The GTO stacks were first connected in parallel to the loads and the arc currents were snubbed for a short time just before the accel voltage was applied. In this case, the current rise of the arc after the sunb was too fast to keep the accel voltage constant and overshoot of the arc current was inevitable. These two effects made the source condition overdense and in turn were apt to cause an electrical instability characterised by a sudden transition to a state in which the gradient grid voltage is almost equal to the accel voltage.[8),13] The GTO stacks were then connected in series to the loads as shown in Fig. 1 and the beam initiation from the underdense side was adopted, eliminating this instability. The GTO valves in the arc power supplies also have the function of cutting off the output currents to the filament when filament arcing is detected. Arcing is detected by monitoring the unbalance of arc currents flowing through each filament.[14]

Each filament power supply is composed of 8 sets of DC output, one for each filament. The negative arc terminal is connected to each positive terminal of the filament power supply in order to reduce inequality of the total current over each filament.

A vacuum tube is used as a regulator/switch valve in the suppressor grid power supply. In JT-60 NBI, GTO valves are planned to be used also in suppressor grid power supplies.

2.3 Time sequence

A typical timing chart of the prototype unit is shown in Fig. 2. The most notable point is the relation between the initiation of the arc and accel power supply outputs. Perveance matched beam initiation has long been understand to be an ideal way of avoiding breakdown during beam initiation phase. This initiation method requires fine timing adjustments and also accurate control of the arc power and accel voltage waveforms and, practically, operating without manual adjustment does not seem achievable for various operating conditions. Judging from our experience of both perveance matched and mismatched beam initiations, however, we believe that source plasma build up in the presence of a constant accel voltage induces less frequent breakdowns. In this mode of operation, the accel voltage is applied first and after it reaches a steady state, the arc current is switched on with a comparatively slow rise time. With this method, a fraction of the ion beam hits the accelerator grids and hardens the periphery of extraction apertures. We believe this process contributes to the elimination of breakdowns at high voltages and at deviated conditions. This may be true in circular hole accelerator like our sources but not in slot-type aperture accelerators because slots form stronger electrostatic lenses than circular holes do and it seems that at the beam initiation phase too much beam strikes the electrodes to avoid producing breakdowns.[15)]

2.4 The ion sources

The prototype ion sources for JT-60, having 80% proton ratio, were first used in the prototype unit and then were replaced by the advanced ion sources, having more than 90% proton ratio. All data in the next section were obtained with the advansed ion sources. These configuration is almost the same as that of the high proton-ratio large volume bucket source.[16)] Here, we briefly describe the advanced ion sources with the view point of electrical consideration.

The large volume arc chamber, made of copper, serves as the anode, and eight hair-pin shaped tungsten filaments in each source are the electron emitters. Molybdenum plates are used for the plasma and gradient grids and oxigen-free copper plates are used for the suppressor and exit grids. Each grid has 1020 shaped apertures within an area of 12×27 cm. The aperture diameter of the plasma and gradient grids is 4 mm and that of the suppresor and exit grids 4.4 mm. The apertures of the suppressor grids are displaced to focus ion beamlets on a focal point which is 8.3 m from the ion sources. Aperture shape and displacement, which may affect the electrical characteristics of the accelerators, is considered in another paper.[17)] The gap widths between electrodes from the arc chamber side are 5, 6.5, 2.5 mm. The grid surfaces facing to first and second gaps are mirror-finished by electrolytic-abrasive polishing method.

3. Results of Performance Test

Testing of the GTO valve was performed for two months. At first, the L-R-Diode element was located at the input side of the GTO valve, this differs from Fig. 1. In this case, we found that several GTO's and surge absorbing diodes connected in parallel to each GTO, not shown in Fig. 1, were subject to damage. One reason for it was found to be a voltage drop of the control power supply for the GTO valve during the pulse. The average control voltage was then increased as a countermeasure. Another possible reason was thought to be the surge current from the stray capacitance of the control power supply during source breakdown. Therefore, the location of the GTO valve and the L-R-Diode element was exchanged as in Fig. 1. After these countermeasures the system was operated for many shots including short pulse, 100 kV and relatively low voltage, 10 sec operations and no failure was observed.

Apart from system reliability, on/off characteristics of the GTO valve may have definite role for the operation of NBI. Figure 3 a) is overall waveforms of the accel and suppressor grid power supplies for a very short pulse. The operating condition is 90 kV, 5 - 25 A, 35 ms with one ion source. An explanation of the voltage and current subscripts are given in Fig. 4. The accel and suppressor grid voltages are initiated at time 'a', while the arc or the accel current is initiated at time 'c' and then increases slowly due to the 1 mH inductance in the arc power supply (see Fig. 1). Surge-like currents at time 'a' flow to charge the stray capacitance. From timing 'a' to 10 ms after time 'c', several GTO's in GTAR are off, therefore, V_{acc} is smaller than V_{in}. At time 'b', V_{acc} increases stepwise as more ATO's in GTAR are turned on to regulate V_{acc} near its preset value. Once all GTO's in GTAR are turned on, the GTO valve does not regulate the output voltage. Therefore, ripples exist on V_{acc}, V_g, and I_{acc} but are not of a level of harmful to the beam characteristics. All outputs of the power supplies are off at time 'd' or, more exactly, the arc is turned off just before V_{acc}, V_g, and V_s are turned off. If all the power supplies are turned off at the same time, then V_{acc}, V_g, and V_s decay faster than I_{acc} and unnecessary breakdowns will occur because the source condition becomes overdense.

Figure 3 b) is time-expanded waveforms at time 'a'. As the stray capacitance between the potentials of V_{acc} and V_g is larger than that between the potentials of V_g and the ground, V_g follows almost the same evolution as V_{acc} and I_g flows in the negative direction (from the ion sources to the power supply) during this phase. Therefore, the electrical instability mentioned in 2.2 may easily occurs if perveance matched beam initiation is used. Abrupt changes of the currents at 120 μs after time 'a' are due to turn-on of the diode in the L-R-Diode element.

Figure 3 c) shows time-expanded waveforms at time 'c'. Although there exist the inductances of 1 mH in the arc power supplies, I_{acc} increases stepwise and V_{acc}, V_g, and V_s dip at time 'c'. We empirically found that to prevent unnecessary breakdowns it is essential to minimize these dips. The large dips of V_{acc} and V_g results in overdense operation of the ion sources and the dip in V_s causes an increase in the amount of backstreaming electrons. With our ion sources, keeping V_{acc} and V_g higher than one-half of their present values and V_s higher than 300 V is necessary for stable beam initiation. Figure 3 c) shows the waveforms for operation of one ion source. When two ion sources are operated, the dips are doubled and, therefore, exeed their permissible levels. It is possible to decrease the dip of V_s by changing the value of the resistor connected to the anode of RTD (see Fig. 1) and by adjusting the gain of RTD feedback loop, which also results a decrease of the dips of V_{acc} and V_g due to the suppression of backstreaming electrons hitting the plasma and/or gradient grids. Instead, for the ease of modification, arc-on timing of one ion source was delayed by 120 μs compared with the other so that the dips occur two times, but each is small enough to maintain stable beam initiation.

Figure 3 d) shows the waveforms with a breakdown. At time 'e', a breakdown occurs and the outputs of the arc, accel, and suppressor grid power supplies are interrupted immediately. Just after time 'e', the accel and suppressor grid power supplies restart while the arc power supplies are turned on at time 'f'. The arc-off time width after breakdown, which is T_{4A} in Fig. 2, is set, in the present particular figure, longer than its normal value for the observation of the waveforms. The effectiveness of the regulation function of GTAR is clearly shown by this figure. Namely, V_{in} shows a sharp overshoot, while V_{acc} does not. The rise time of I_{acc} is about 50 ms, which is much slower than conventional test stands but fast enough for JT-60 as the JT-60 plasma may have a much longer confinement time. Figure 3 e) is a time-expanded waveform of I_{acc} at breakdown. At 0 μs, V_{acc}, V_g, and V_s are initiated. At 290 μs, the arc is turned on and, almost at the same time, a breakdown occurred. The current from 290 μs to 320 μs is the contribution from the stray capacitance, which is damped by both the resistors located on the second winding of the surge block core and at the anode of the bypass diode D1 (see Fig. 1). The rising current from 320 μs to 350 μs is from the filter capacitor of 30 μF in the input side of the GTO valve. The current rise time is determined by the inductance of 0.3 H located at the cathode of the GTO valve. It takes up to 60 μs to cut the fault current after breakdown but in our experience this is not deleterious to the voltage holding ability of the electrodes. We believe that this is due to the low value of the fault current. The damge patterns caused by breakdown, which are present on the positive surfaces only, are discolored circles of about 4 mm diameter. The shut off time can be shortened, in principle, to the GTO's turn off time (20μs) by modifications of gate circuits and signal transmission line, but this effort seems unnecessary.

Figure 3 f) is time-expanded waveforms during the beam off phase. At time 'd'', the arc is turned off, while V_{acc}, V_g, and V_s are turned off at time 'd'''. Therefore, the ion sources operate in the underdense condition during the beam off phase as well as the beam on phase. After time 'd'' until time 'd''', V_{acc} is too high due to circulating current in the L-R-Diode element but breakdowns rarely occur because the time width is so short. The gradient grid and the suppressor grid currents increase due to the perveance mismatched condition during the falling down phase of the accel current.

It is known that ion sources generally need 'long pulse conditioning' as well as 'high voltage conditioning' to achieve high voltage and long pulse operation without breakdown. Figure 4) is an example of long pulse conditioning shot after high voltage conditioning was completed at a level of 100 kV, 80 A, 0.5 s. There are 9 breakdowns even at lower voltage operation. These breakdowns seem to take place at random, independent of the current rising phase. This means that mismatched beam initiation from the underdense side does not cause additional breakdowns. In Fig. 4, it takes as long as 2 s until the accel current becomes constant. This is due to the thermal long time constant of the filament, which are heated by the arc currents, as we use relatively thick filaments. This time constant can be shortened by the modification of the ion sources.[18)]

4. Conclusion

A regulator/switch vacuum tube in the accel power supply of the prototype injector unit for JT-60 was replaced by a GTO valve. This solid state valve was tested for reliability and applicability. The perveance mismatched beam initiation with slow arc rise time was found to be well matched with the use of the GTO volve. The relatively long turn off time of the GTO element does not seem deleterious to ion source performance.

Acknowledgements

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References

1) S. Matsuda et al., a paper presented at 4th Int. Sympo. on Heating in Toroidal Plasmas, Rome, March 21-28, 1984.
2) T. Shibata et al., Proc. of 10th Sympo. on Eng. Problems of Fusion Res., Philadelphia, Dec. 5 - 9, 1983, pp.2031 - 2035.
3) M. Akiba et al., Rev. Sci. Instrum. 53, 1864 (1982).
4) Y. Ohara, Proc. of 7th Sympo. on Ion Sources and Ion Assisted Tech., Kyoto, Sept. 12 - 16, 1983, pp.447 - 458.
5) M. Akiba et al., Proc. of 10th Sympo. on Eng. Problems of Fusion Res., Philadelphia, Dec. 5 - 9, 1983, pp.2021 - 2025.
6) H. Horiike et al., Rev. Sci. Instrum. 55, 332(1984).
7) Y. Okumura et al., a paper presented at 4th Int. Sympo. on Heating in Toroidal Plasmas, Rome, March 21 - 28, 1984.
8) M. Matsuoka et al., Proc. of 12th Sympo. on Fusion Tech., Jülich, Sept. 13 - 17, 1982, pp.1361 - 1366.
9) O. Kaneko et al., Proc. of 10th Sympo. on Eng. Problems of Fusion Res., Philadelphia, Dec. 5 - 9, 1983, pp.1502 - 1506.
10) I. Hashimoto et al., presented at the meeting of the Institute of Electrical Engineers of Japan at Okayama, April 4 - 7, 1983.
11) M. Kuriyama et al., Proc. of 9th Sympo. on Eng. Problems of Fusion Res., Chicago, Oct. 26 - 29, 1981, pp.1347 - 1351.
12) M. Matsuoka et al., to be published in the IEEE Trans. on Plasma Sci.
13) R. Becherer et al., EURATOM Report EUR-CEA-FC-1147, March 1982.
14) S. Tanaka et al., 8th Sympo. on Ion Sources and Ion-Assisted Tech., Tokyo, June 4 - 6, 1984.
15) W. S. Cooper, Lawrence Berkeley Laboratory Report LBL-12673, April 1981.
16) Y. Okumura et al., Rev. Sci. Instrum. 55, 1(1984)
17) M. Matsuoka, to be published.
18) S. Tanaka, to be published.

Table 1 Fundamental Specifications of the Power Supply System of the Prototype Injector Unit for JT-60

	Voltage	Current	Duration	Duty
Accel P.S.				
plasma grid	20-100 kV	80 A	10 s	1/30
gradient grid	20-90 kV	-2 - +2 A	10 s	1/30
Suppressor Grid P.S.	-(.5-3) kV	22 A	10 s	1/30
Arc P.S.	120 V	2000 A × 2	10.5 s	-
	or 180 V	1000 A × 2		
Filament P.S.	12 V	400 A × 8 × 2	14 s	-

Table 2 Specifications of the Gate Turn Off Thyristors

		Accel P.S.
Type		SG600EX21 (Toshiba)
Voltage Range	(V)	2500
I_T(RMS)	(A)	420
L_{TGQ}^{*}	(A)	600
I_{TSM}^{**}	(A)	6000
t_{gq}^{***}	(μs)	20

* turn off current

** surge on current

*** turn off time

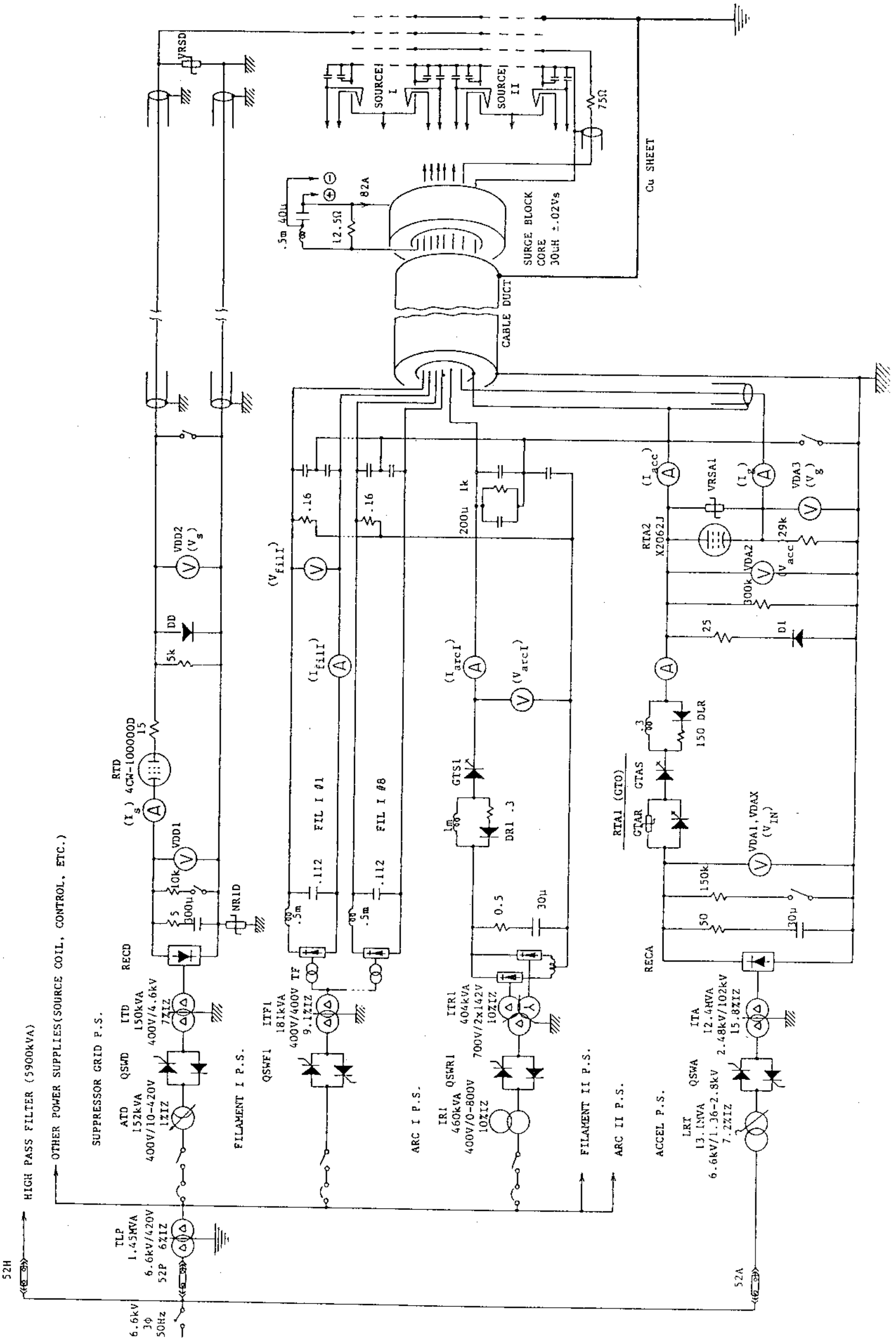

Fig. 1 A schematic diagram of the power supply system of the prototype injector unit for JT-60.

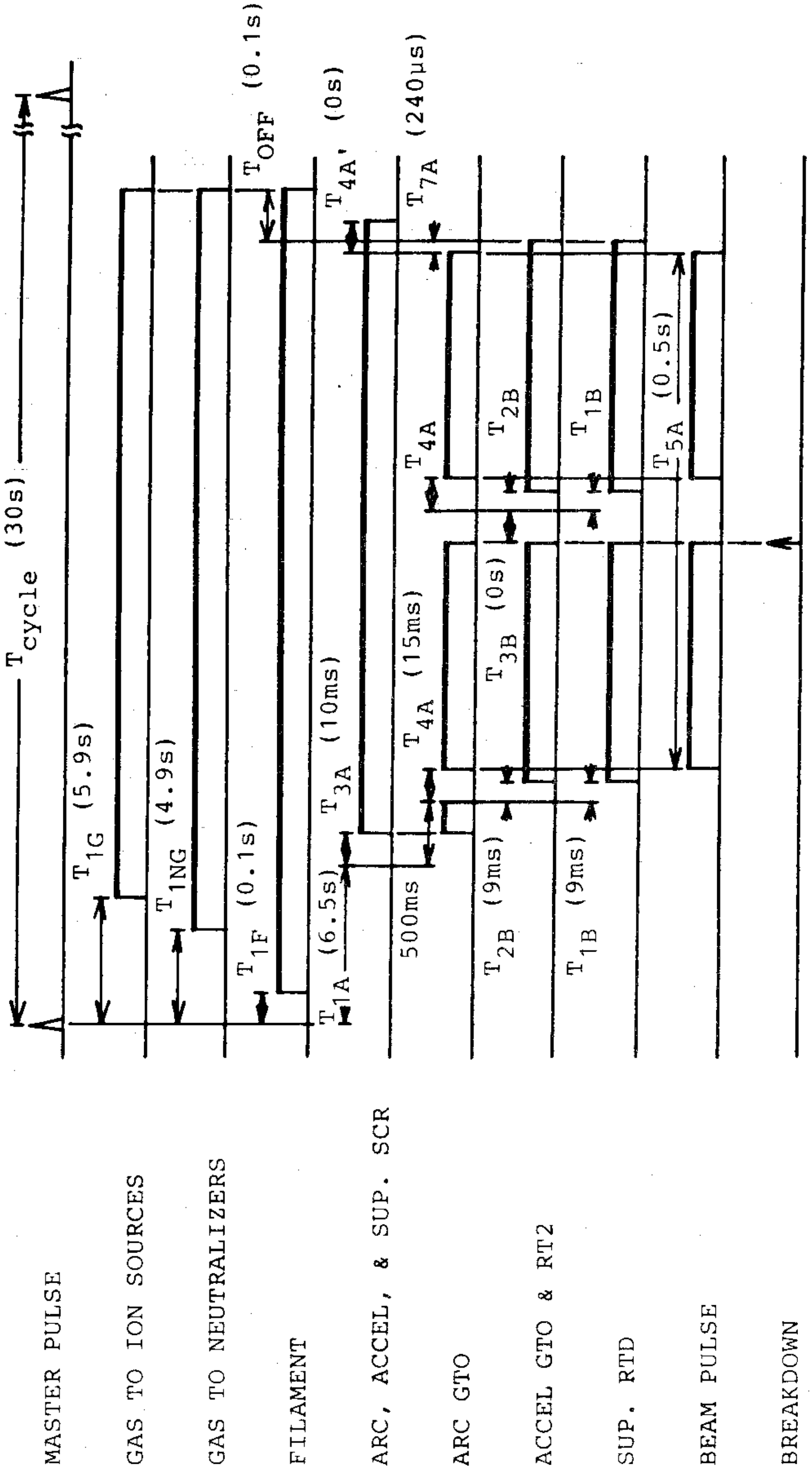

Fig. 2 A typical timing chart of the prototype unit.

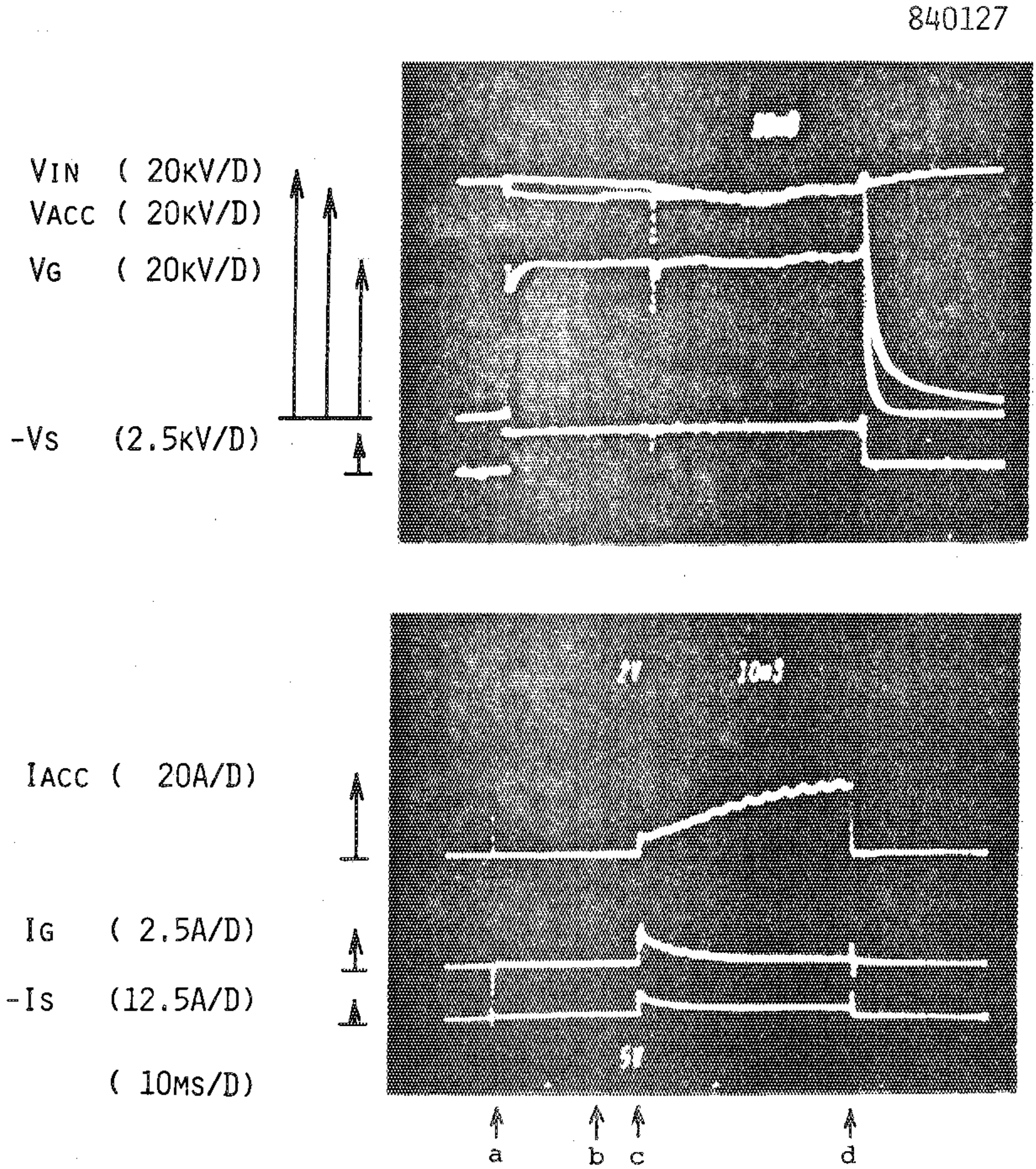

Fig. 3 a) Overall waveforms of the accel and suppressor grid power supplies. The operating condition is 90 kV, 5 - 25 A, 35 ms with one ion source.

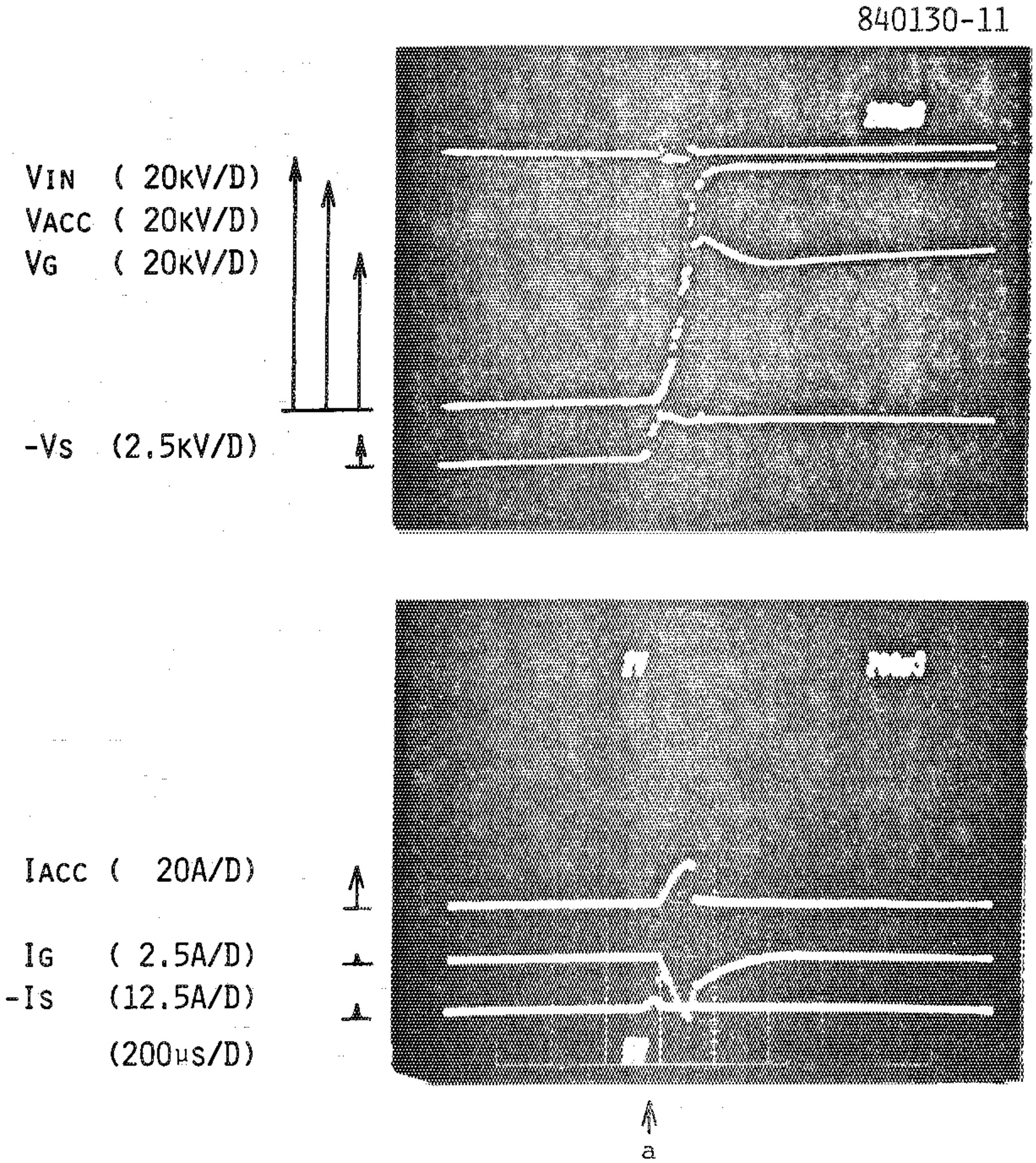

Fig. 3 b) Time-expanded waveforms at the start of the accel and suppressor grid power supplies.

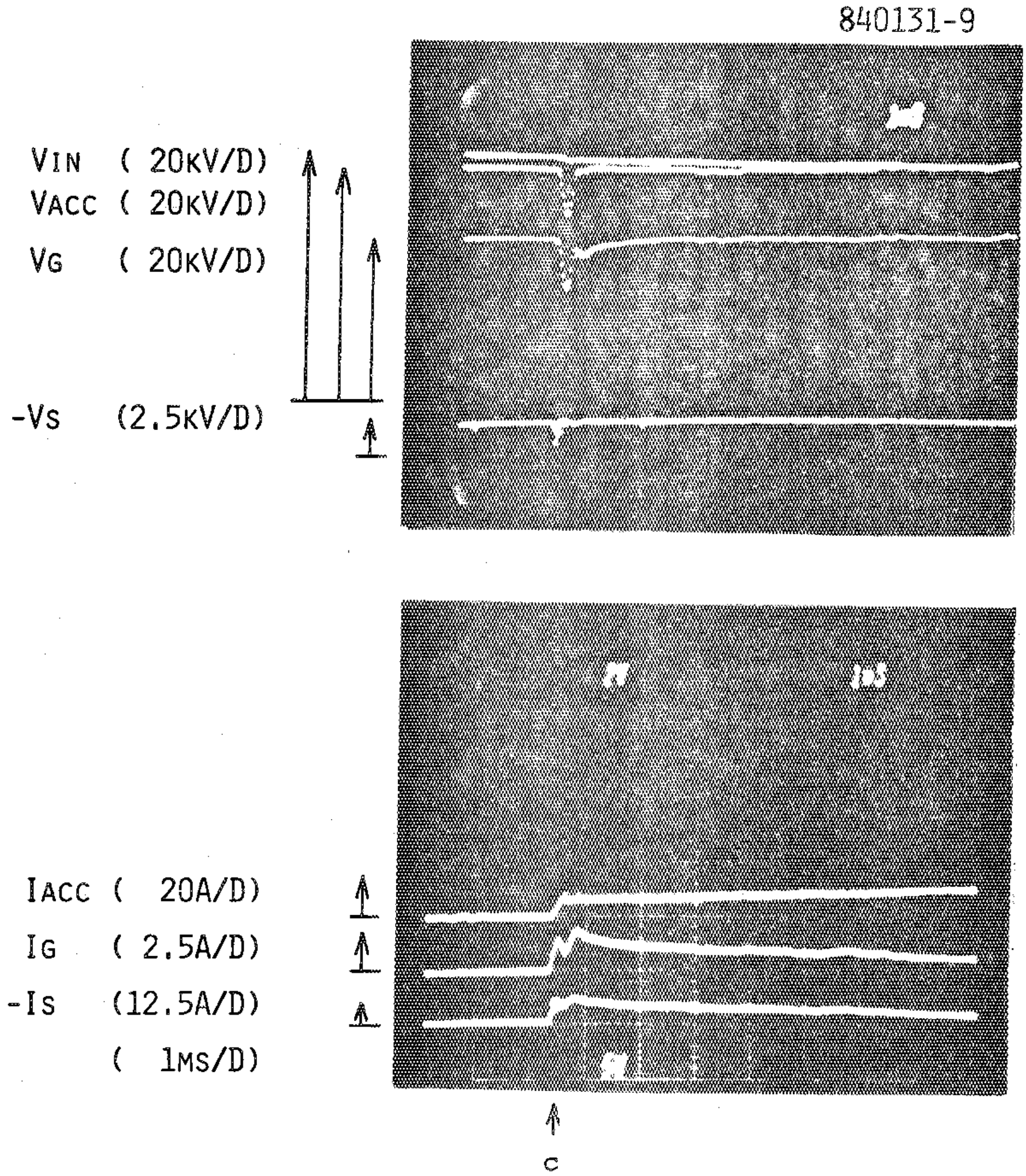

Fig. 3 c) Time-expanded waveforms at the start of the arc or the accel current.

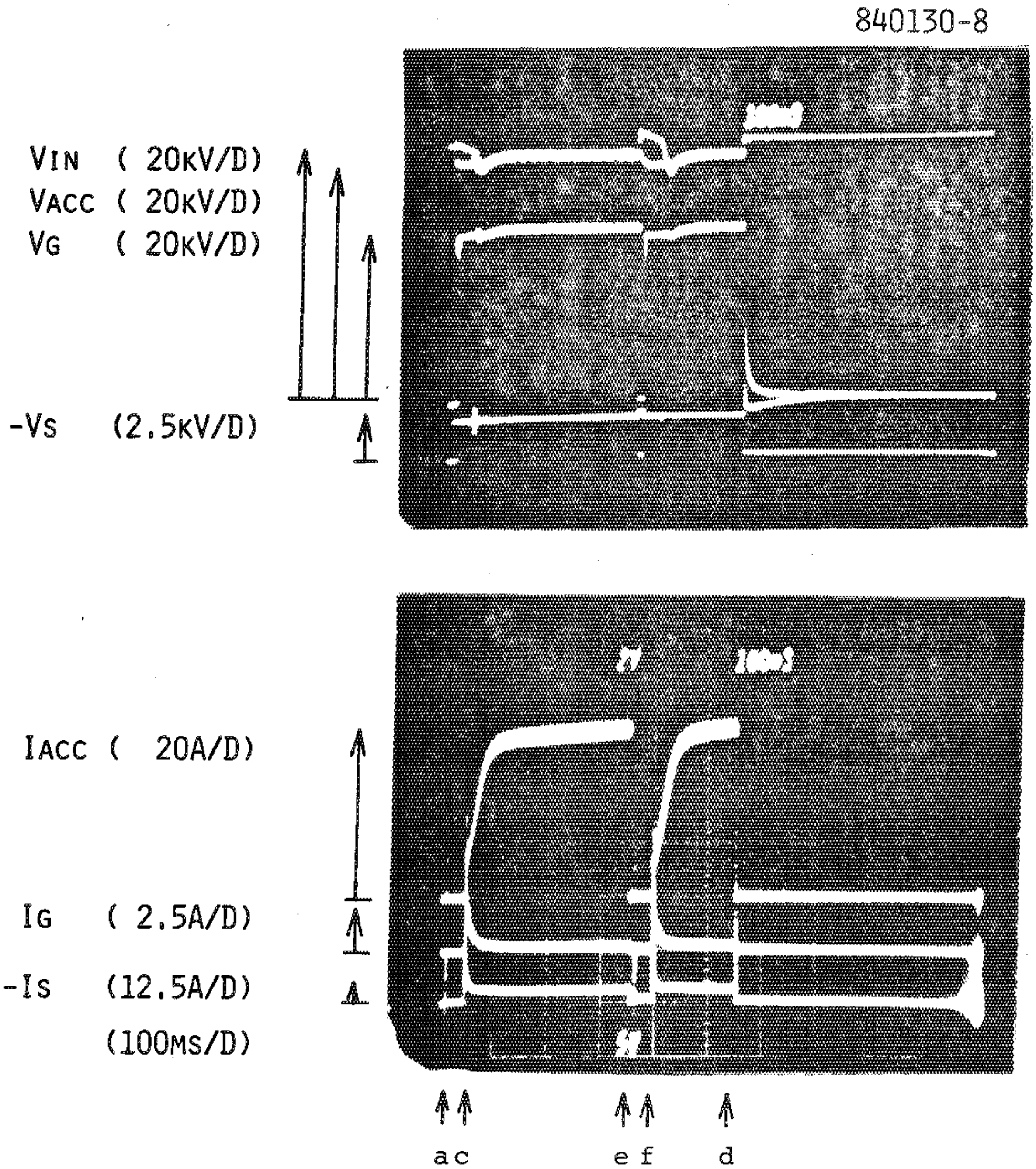

Fig. 3 d) The waveforms with a breakdown. The operating condition is 90 kV, 60 A, 0.5 s with two ion sources.

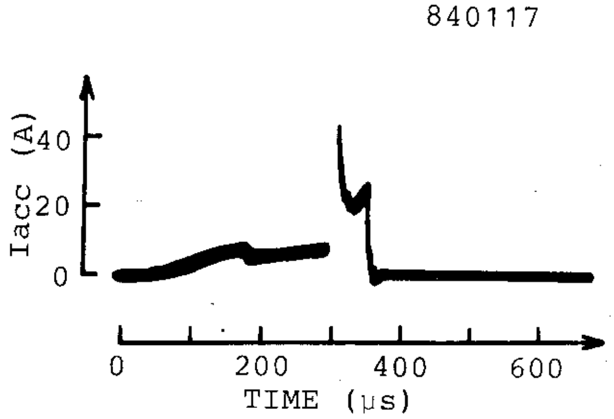

Fig. 3 e) A time-expanded waveform of accel current at breakdown. At 0 μs, V_{acc}, V_g, and V_s are initiated. At 250 μs, the arc is turned on and, almost at the same time, a breakdown occurred. The fault current is cut at 350 μs by a GTO valve.

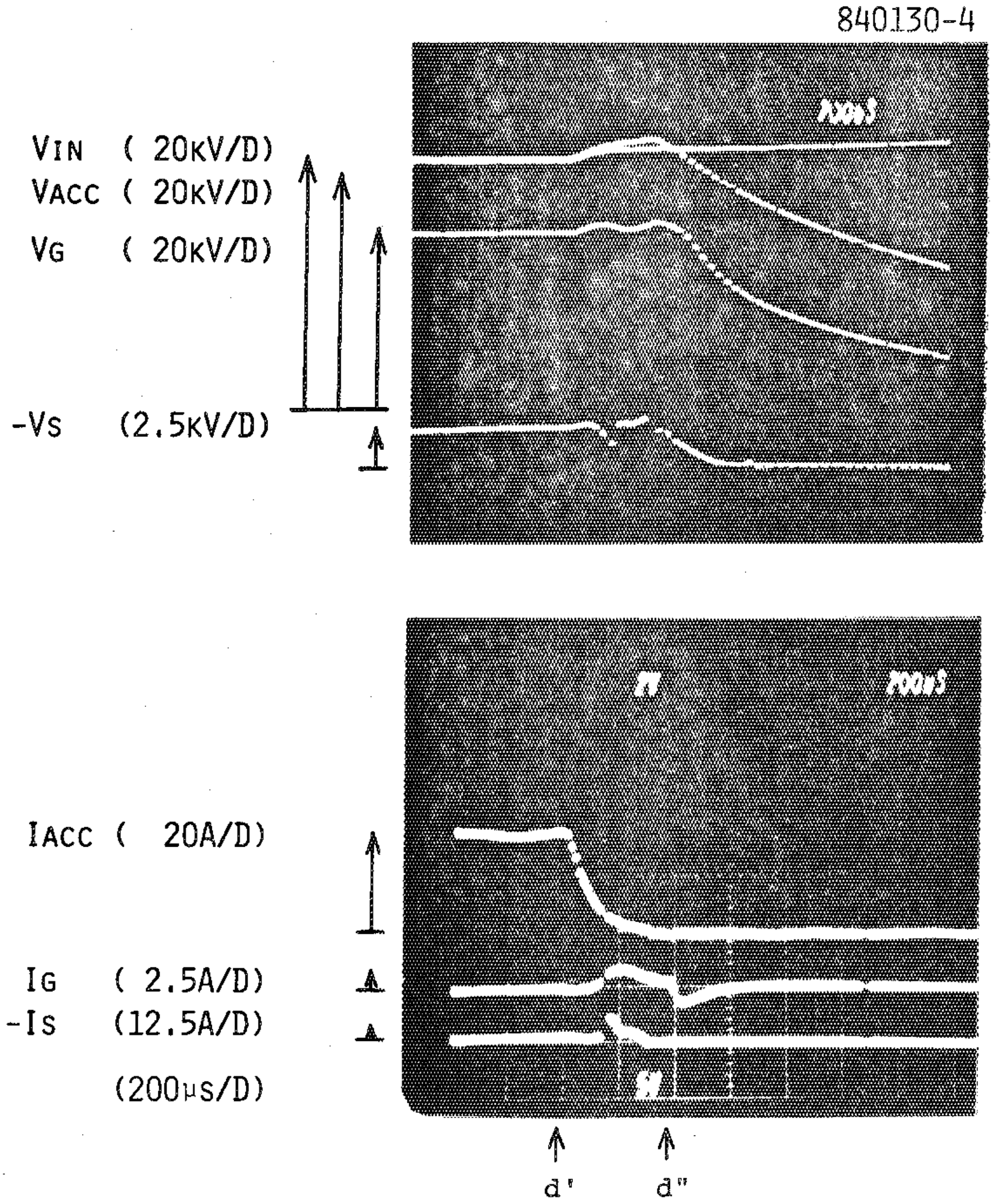

Fig. 3 f) Time-expanded waveforms at normal beam off phase. The arc is turned off at time 'd'' while V_{acc}, V_g, and V_s are turned off at time 'd"'.

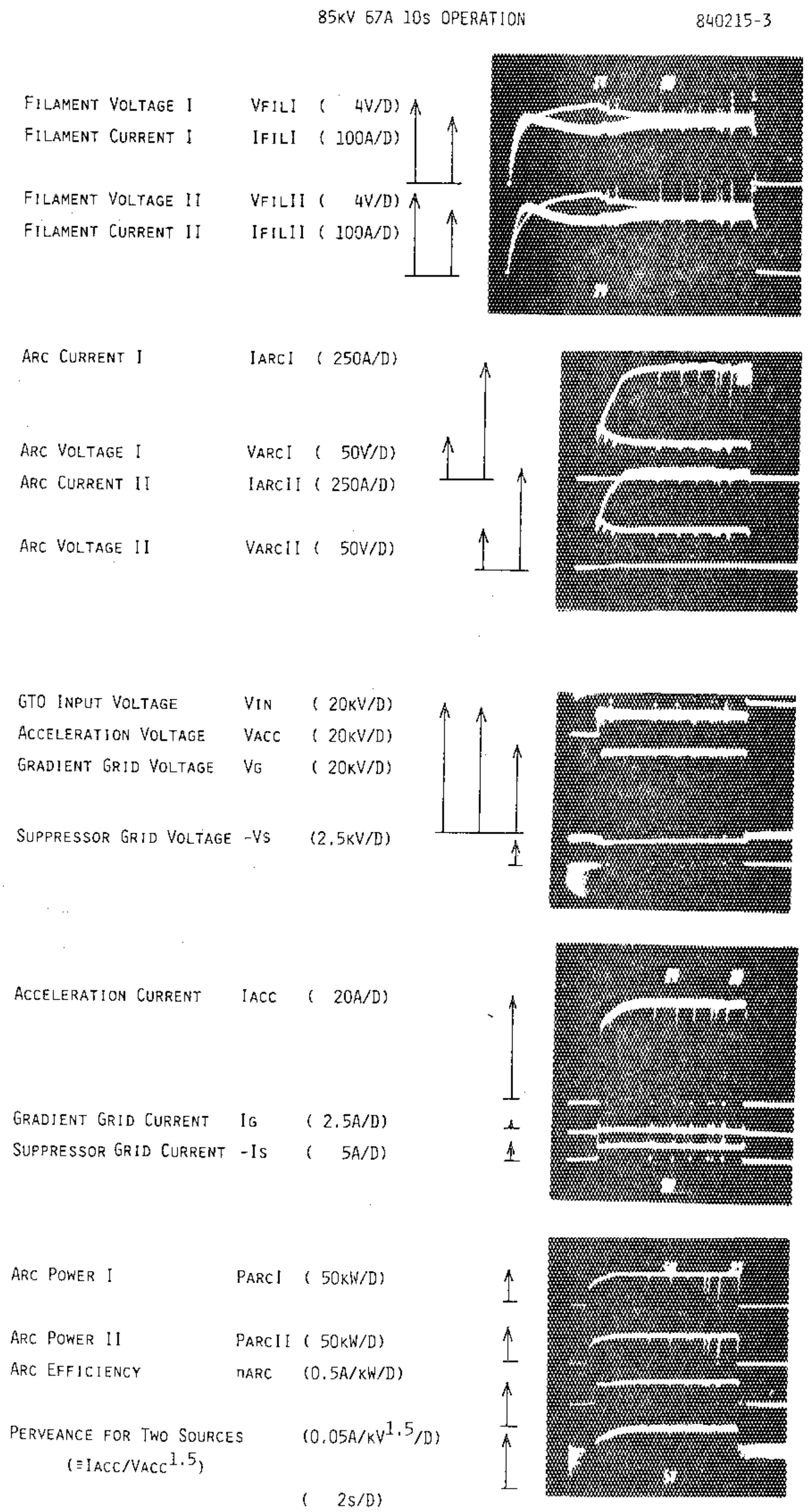

Fig. 4 An example of long pulse conditioning shot. There are 9 breakdown, which seem to take place at ramdom, independent of the current rising phase.