KFKI-1982-97

K. RÓZSA
G. RUBIN
M. JÁNOSSY
P. APAI
KAN-ICHI FUJII

ON THE GLOW-TO-ARC TRANSITION IN HIGH CURRENT AL HOLLOW CATHODE DISCHARGES

Hungarian Academy of Sciences

CENTRAL RESEARCH INSTITUTE FOR PHYSICS

BUDAPEST

KFKI-1982-97

ON THE GLOW-TO-ARC TRANSITION IN HIGH CURRENT AL HOLLOW CATHODE DISCHARGES

K. Rózsa, G. Rubin, M. Jánossy, P. Apai

Central Research Institute for Physics
H-1525 Budapest 114, P.O.B. 49, Hungary

Kan-ichi Fujii

Ibaraki University, Hitachi-shi, Ibaraki, Japan
(visiting scientist at CRIP, Budapest)

HU ISSN 0368 5330
ISBN 963 371 996 8

ABSTRACT

The glow-to-arc and arc-to-glow transitions were studied in d.c. hollow cathode discharges using Al cathode in pure He and in He-Kr mixture. The discharge parameters (p=20-40 mbar, I=1-2 A in a 100 mm long 3 mm diameter hollow cathode) correspond to the working conditions of the He-Kr laser.

In the seemingly quiet glow discharge short arcs (~μs) were found and studied as a function of discharge parameters. It was possible to show that a real arc-free discharge can be maintained even in the current region of the hollow cathode.

A possible mechanism of arc formation in Al hollow cathode discharge is discussed to explain the difference between stability of the discharges having oxide coated or clean metal cathode surfaces. The effect of impurities or a low ionization component (krypton) in He buffer gas is also considered.

АННОТАЦИЯ

В чистом He и смеси He-Kr исследовались переходы из тлеющего в дуговой и из дугового в тлеющий разряд с использованием полого алюминиевого катода. Параметры разряда (p=20-40 мбар, I=1-2 A, длина трубки 100 мм, диаметр катода 3 мм) соответствовали рабочим условиям He-Kr лазера.

В области тлеющего разряда были обнаружены и изучены короткие дуговые разряды (длительностью ~микросекунды) в зависимости от параметров разряда.

Показана возможность поддержания разряда без возникновения дуговых процессов и в токовой области полого катода. Обсуждены возможные механизмы возникновения дуговых разрядов в разрядах с полым алюминиевым катодом для объяснения различной стабильности разрядов с чистым катодом и катодом с окисленной поверхностью, а также вопросы ионизации компонентов в буферном газе.

KIVONAT

Tiszta héliumban és He-Kr keverékben tanulmányoztuk a ködfénykisülésből az ivelésbe, illetve az ivelésből a ködfénykisülésbe való átmeneteket egyenáramu üreges katódu kisülésben, Al-katód esetében. A kisülési paraméterek (p=20-40 mbar, I=1-2 A, egy 100 mm hosszu és 3 mm átmérőjü üreges katódban) a müködő He-Kr lézer feltételeinek feleltek meg.

A látszólag normális ködfénykisülésben rövid iveket (~μsec) találtunk, melyeket a kisülési paraméterek függvényében tanulmányoztunk. Sikerült megmutatni, hogy egy valódi ivmentes kisülés tartható fent, még az üreges katódnak megfelelő áramtartományokban is.

Az Al-üreges katódu kisülésben az ivképződés egy lehetséges mechanizmusát diszkutáltuk abból a célból, hogy a tiszta fémfelületü üreges katódbeli és az oxidréteggel bevont felületü üreges katódbeli, illetve szennyezések vagy alacsony ionizációs potenciálu komponensek (Kr) jelenlétében végbemenő kisülés stabilitása közötti eltérést értelmezzük.

1. INTRODUCTION

It is known that current fluctuation, i.e. current noise, is much less in hollow cathode lasers than in conventional positive column lasers [1]. On the other hand, arcing limits the current and the discharge becomes unstable and contracts into an arc at a certain current. In several cases no saturation of laser power with current can be observed due to this phenomena [2]. Arcing may be considered as one of the main obstacles to constructing practical hollow cathode lasers.

Several experiments have been carried out to prevent arc formation using either a modified anode structure [3,4] or a divided cathode region [5]. Most of these experiments considered an arc with a length of some millisecond or even longer. However, in the construction of hollow cathode lasers no transition into even shorter arcs is allowed if we assume a reasonable lifetime for these lasers. Fast transitions between glow and arc and returning to glow have been reported by Seeliger [6] and studied in detail by Suginuma and Nogaki [7,8]. In the light of their experiments short arcs may be expected in high current hollow cathode discharges as well.

In the present paper we report measurements on arcs with lengths of the order of some μs as a function of different discharge parameters. We have been able to show that it is possible to build up a completely arc-free discharge at the high pressure and current needed for hollow cathode lasers. In the natural oxide coated Al hollow cathode we found rather poor stability; however, if the discharge is burnt for several days the oxide coating disappears due to the cathode sputtering and excellent stability was found as a result of the clean metal surface.

2. EXPERIMENTAL SETUP AND MEASUREMENTS

The construction of the discharge tube was a modification of the edge protected discharge tube described in ref. [5] ensuring that no discharge can flow from the edges of the cathode and, except for the cathode hollow, no other part of the cathode can be covered by discharge. The water cooled hollow cathode was made of 99.9 % purity Al having a length of 100 mm, and a diameter of 3 mm, the anode was of stainless steel.

The experimental arrangement is shown in Fig. 1. The vacuum and gas filling system was suitable for vacuums to 10^{-7} mbar and for filling gases of spectroscopic purity.

The optical system was utilized to monitor the intensities of different spectral lines including those of the impurities coming from the electrodes. The tube was cleaned by filling it with some 15 mbar He, running the discharge and then evacuating the tube. These processes were repeated for several days until the gas remained clean during the discharge. Then, apart from the He and Al lines, mainly H lines could be detected, the intensity ratio He 587.6 nm/H_{α} being 200-500 depending on current and gas pressure.

The electronic measurement circuit was designed to measure the transition from glow-to-arc, the returning to glow and the length of the arcs. The discharge current was monitored with a help of a 1Ω low inductance precision resistance (3) and by DVM, the voltage of the discharge was measured by using a precision high frequency compensated voltage divider (4) and DVM. The transient of the voltage and current due to the influence of transition from glow-to-arc and the returning to glow was studied by a 10 MHz two-channel transient recorder (6). The length of arcs was analysed and stored by a time analyser (7), the statistics of the arcs were calculated and displayed by a personal computer (8). Analyser (7) also served to protect the discharge tube (1) against long arcs by giving a signal for switching off the power supply (2). As the transient time of arc voltage and current signal occured in the 10-100 ns region, coaxial cable with a 50Ω terminator was used.

It was thought that arcing might be preceeded by current noise due to the fluctuation of the ion density in the discharge [5]. With the help of the transient recorder it was possible to check the current and the voltage signal before the transition into arc. In our measurements no significant noise was observed either on the total current or on the voltage before arcing occured. This measurement, however, cannot be regarded as experimental proof. Since the voltage hardly depends on current density it may well be the case that local current fluctuations cannot be seen on the total current and on the voltage. Current density measurements on parts of the cathode surface as well as optical measurements on light intensity fluctuations along the hollow cathode could be suitable to clarify this problem.

Typical arcs measured by a two channel transient recorder are shown in Fig. 2a, b, and c.

In Fig. 2a it can be seen that even short arcs (sometimes shorter than 1μs) show similar characteristics to long arcs having a voltage drop below 50 volts and the current is determined by the resistance of the electrical circuit. Figure 2b shows a "double" arc; the discharge returns to glow only for about 1μs. It often happens that when the arc stops the discharge also stops for a short time and then the glow discharge starts again - as can clearly be seen in Fig. 2c. Sometimes, perhaps due to the incoming impurities or to the change of the cathode surface after an arc, a series of arcs (the number being of the order of 100 within a few seconds) followed each other, even in an otherwise relatively stable discharge.

The arcs were counted and analysed according to their duration (τ) and placed into the different channels (Table 1).

Table 1

Different time channels for analysing arcs

Channel code	Duration of arcs
0	$\tau < 1\ \mu s$
1	$1\mu s < \tau < 10\mu s$
2	$10\mu s < \tau < 100\mu s$
3	$100\mu s < \tau < 330\mu s$
4	$330\mu s < \tau < 1$ ms
5	1 ms $< \tau < 10$ ms
6	10 ms $< \tau < 33$ ms
7	33 ms $< \tau$: power supply OFF

In a clean gas still having the oxide coating only short arcs occurred at relatively low current, the number of arcs rapidly increased with increasing current, and the length of arcs also increased. Table 2 shows the result of a series of measurements in 21 mbar He between 200 and 400 mA. With each current value fixed 600 arcs were measured.

Table 2

Results of measurements on arcs in Al_2O_3 coated hollow cathode as a function of discharge current

Current (mA)	Measurement time	Number of arcs			
		0-1μs	1-10μs	10-100μs	100-330μs
200	91'09"	21	578	1	0
250	26'43"	9	591	0	0
300	10'48"	3	597	0	0
350	2'40"	0	597	3	0
400	1'57"	0	580	20	0

The "optimal" pressure, i.e. the pressure where the highest current can be achieved without arcing, was found between 30-35 mbar having the critical current 400-500 mA.

In our previous paper [5] in a 7 mm diameter hollow cathode the optimal pressure was found to be 13 mbar and it was predicted that with a smaller diameter the optimal pressure may be proportionally higher, giving a constant p·d value, where p is the gas pressure and d is the hollow cathode diameter. The present measurement seemingly agrees with this statement.

Having burnt the discharge for several days the oxide coating disappeared in a relatively short time. As the oxide layer disappeared the voltage of the discharge increased and also increased the stability of the discharge. Table 3 shows the parameters in the discharge changing in time, while the current was kept constant (400 mA); the He pressure was 26 mbar.

Table 3

Changing voltage and stability data measured during the disappearing oxide coating in the hollow cathode

Time scale (min)	U (Volts)	arc/min in different time channels (μs)			
		0-1	1-10	10-100	100-330
0	173	0	3.1	3.1	0
7	177	0	0.32	0.32	0.16
28	181	0	0.16	0.08	0
40	184	0	0.06	0	0
60	186		arc free		

The increasing intensity of the different Al lines clearly shows that the changing parameters are really due to the vanishing oxide layer as the Al lines become about three times more intense than they were before. In the cathode sputtered Al hollow cathode laser it was also found that the sputtering yield is increasing with the vanishing oxide coating [9].

The critical arcing current (which was about 0.5 A with oxide coating) became higher than 2 A (which was the highest current investigated) in the 30-35 mbar He, and even having 10^{-1} mbar Kr in the He the critical current still reached the 2 A value. These data are in agreement with the experiments of Suginuma and Nogaki [8] that the glow discharge is much more stable using gold electrodes instead of aluminium, and there is also agreement with the experimental data that in a cathode sputtered hollow cathode Cu laser higher current is available without arcing [10] than in the noble gas mixture hollow cathode laser using Al electrodes, both in half wave rectified a.c. discharge and in d.c. discharge.

3. DISCUSSION

The measured transitions between glow-to-arc and the returning to glow spontaneously occur if the current value reaches the critical arcing current. The critical current depends on different discharge parameters, i.e. the quality and pressure of the gas, the hollow cathode diameter and the material of the cathode. We propose a qualitative model for this phenomenon taking into account the effect of Al_2O_3 film, the impurities in the gas (as well as sputtered atoms and other low ionization components) and thermal effects.

The fact that the oxide coating decreases the necessary voltage needed to maintain the glow discharge is known [11]. Across the thin Al_2O_3 film a high electric field can be built up due to the space charge on one side of the film and the metal surface on the other side. This electrical film can release electrons from the cathode surface while from the pure metal surface the electrons are released due to the bombardment of ions, U.V. photons and energetic particles. The inhomogeneity of the Al_2O_3 film may help to form an arc. Where this film is thinner a higher electrical field exists, the discharge is concentrated on these places and an arc can be developed.

The arc stops mainly due to thermal effects. The gas temperature in the arc can reach a value where the kinetic energy of the particles is too high, the local density of the gas becomes too small to keep the arc any longer. The separating space charges in the arc also work against keeping the arc discharge. The transition from arc-to-glow or the stopping of the discharge may thus be due to thermal and space charge effects. Concentrating more energy in the arc, i.e., having higher current, the lifetime of arcs increases as was found in our experiments. If at the place of the arc spot a clean Al surface remains the next arc is likely to occur somewhere else where the high current density in the glow can still be formed at relatively low voltage.

If impurities of low ionization potential or Kr are present in the tube the critical arcing current decreases on clean metal surfaces as well [5]. These impurities may result in locally concentrated heavy ion space charges bombarding a small area of the cathode surface and increasing the sputtered metal atom concentration in this part of the discharge. These sputtered atoms are also usually of greater mass and lower ionization potential than those of the buffer gas. After the positive feedback of this action a small area of the cathode can be heated to the temperature where thermal electrons are also released. Thus, an arc spot can be formed.

In the case of a clean metal surface with pure noble gas in the discharge the critical arcing current increases and exceeds the 2 A value - the highest current investigated. (At still higher current densities the strong sputtering changes the conditions of the discharge and the He-Kr laser power saturates due to high metal vapour concentration). Here the statistical fluctuation of the ion density may trigger the arc. If there is an ion flow towards one direction a magnetic force also acts between the ions increasing the local ion density until the formation of an arc can be started.

The critical density of ions for starting processes resulting in an arc is supposed as being proportional to the total current, in agreement with the experimental result that arcing on a continuous cathode surface depends on the total current rather than on the current density on the cathode surface [5].

4. CONCLUSIONS

The glow-to-arc and arc-to-glow transitions were measured in a high current hollow cathode discharge in pure He and He-Kr mixture with an Al cathode by means of a rapid electronic measuring technique together with spectroscopic measurements. As a result of our experiments we can conclude the following:

- Given certain conditions short arcs with a duration of 1μs or even shorter can be formed having very similar electrical characteristics to those of long arcs.

- The transient time from a relatively high volume glow into an arc measured by the voltage and the total current of the discharge is in the order of 100 ns.

- The lifetime of the arcs increases with increasing current.

- There exists a critical arcing current below which no arcs can be found. The value of the critical current in a 3 mm diameter hollow cathode at 35 mbar He is 0.2-0.4 A with an oxide coating on the cathode surface; but it is over 2 A with a clean Al cathode. In a mixture of He with 10^{-1} mbar Kr it is 1.8-2 A.

ACKNOWLEDGEMENTS

The work was supported by the State Office for Technical Development. We gladly acknowledge helpful discussions with Prof. F. Howorka (Innsbruck University), Prof. Z. Stenberg (Ruder Boskovics Institute, Zagreb), Drs. K.G. Antal and F. Halász (Tungsram Research Laboratory, Budapest) and with Prof. N. Kroó and Dr. L. Csillag (CRIP, Budapest). Thanks are due to Dr. P. Horváth and Mr. I. Molnár for the help in providing the electrical measuring circuits, to Mr. J. Tóth and Mr. Gy. Császár for the mechanical construction work, to Miss. J. Forgács for the technical assistance, and to Mr I. Pálmai for construction of the power supply and related electronics.

REFERENCES

[1] R.C. Jensen, G.J. Collins, W.R. Bennett: Appl. Phys. Lett. 18, 50 (1971)

[2] J.A. Piper, C.E. Webb: J. Phys. D: Appl. Phys. 6, 400 (1973)

[3] R.D. Ried, J.R. McNeil, G.J. Collins: Appl. Phys. Lett. 29, 666 (1976)

[4] K. Fujii, M. Shimizu, T. Takahashi: Proceedings of Seventh International Conference on Gas Discharges and their Applications, London 1982. p. 398

[5] K. Rózsa: Z. Naturforsch. 35A, 649 (1980)

[6] R. Seeliger: Ann. d. Phys. 5F, B.24 609 (1935)

[7] I. Suginuma, M. Nagaki: I.C.P.I.G. Minsk (USSR) 1981 Contr. Papers p. 767-768

[8] M. Nagaki, I. Suginuma: Sixth Symp. on Ion Sources and Ion-Assisted Technology, Kyoto (1982) p. 1-4

[9] D.G. Gerstenberger, R.D. Reid, G.J. Collins: Appl. Phys. Lett. 30, 466 (1977)

[10] H.J. Eichler, H. Koch, W. Martin, R. Molt, J.L. Qui: Appl. Phys. B26, 49 (1981)

[11] G. Francis: "The Glow Discharge at Low Pressure" in. Handbuch der Physik Vol. XXII. p. 164 (Springer Verlag 1956)

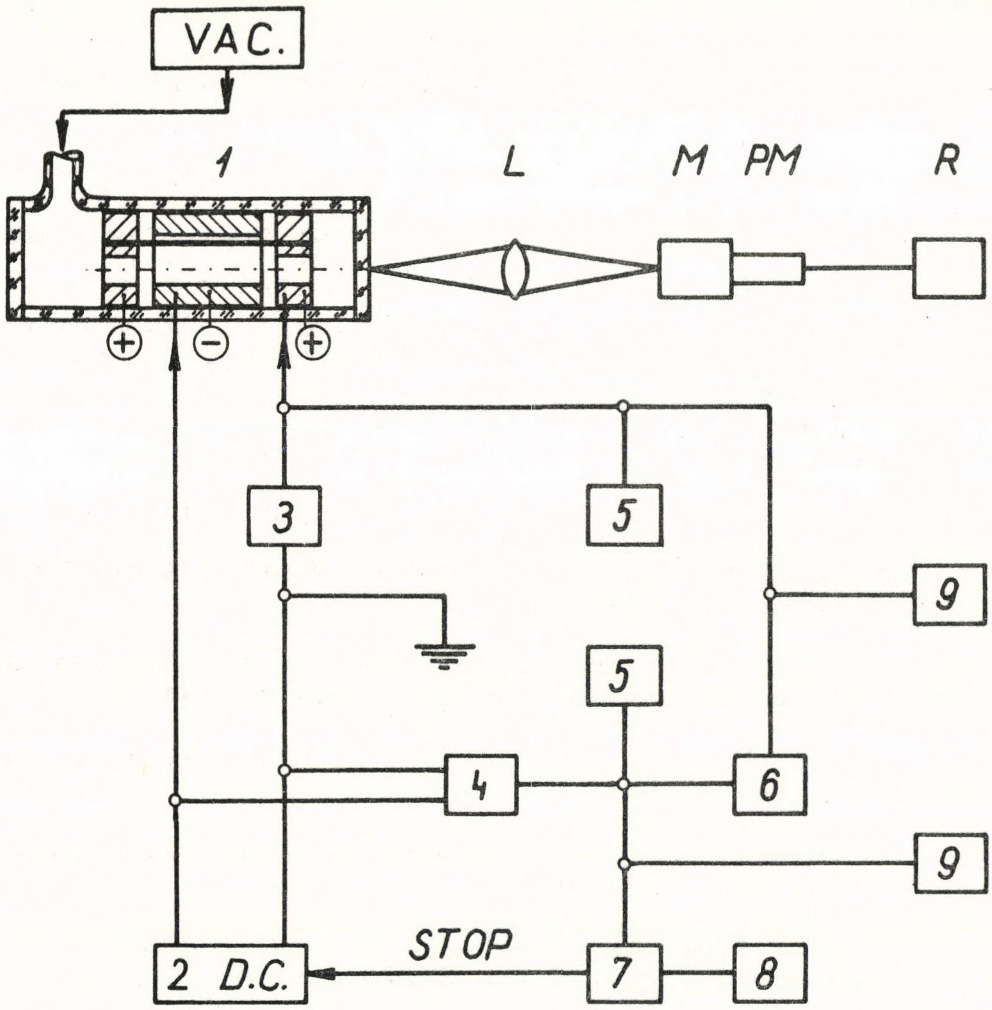

Fig. 1. Experimental setup for analysing arc properties of hollow cathode discharge.
1. edge protected discharge tube; 2. d.c. power supply; 3. 1Ω low inductance, precision for current monitoring; 4. frequency compensated precision voltage divider; 5. digital voltage meters; 6. 10 MHz two channel transient recorder; 7. time analyser for arc statistics and PET computer interface; 8. PET computer; 9. 50 Ω terminators. VAC - vacuum and gas filling system. Optical measuring arrangement: L - lens, M - monochromator, PM - photomultiplier, R - recorder.

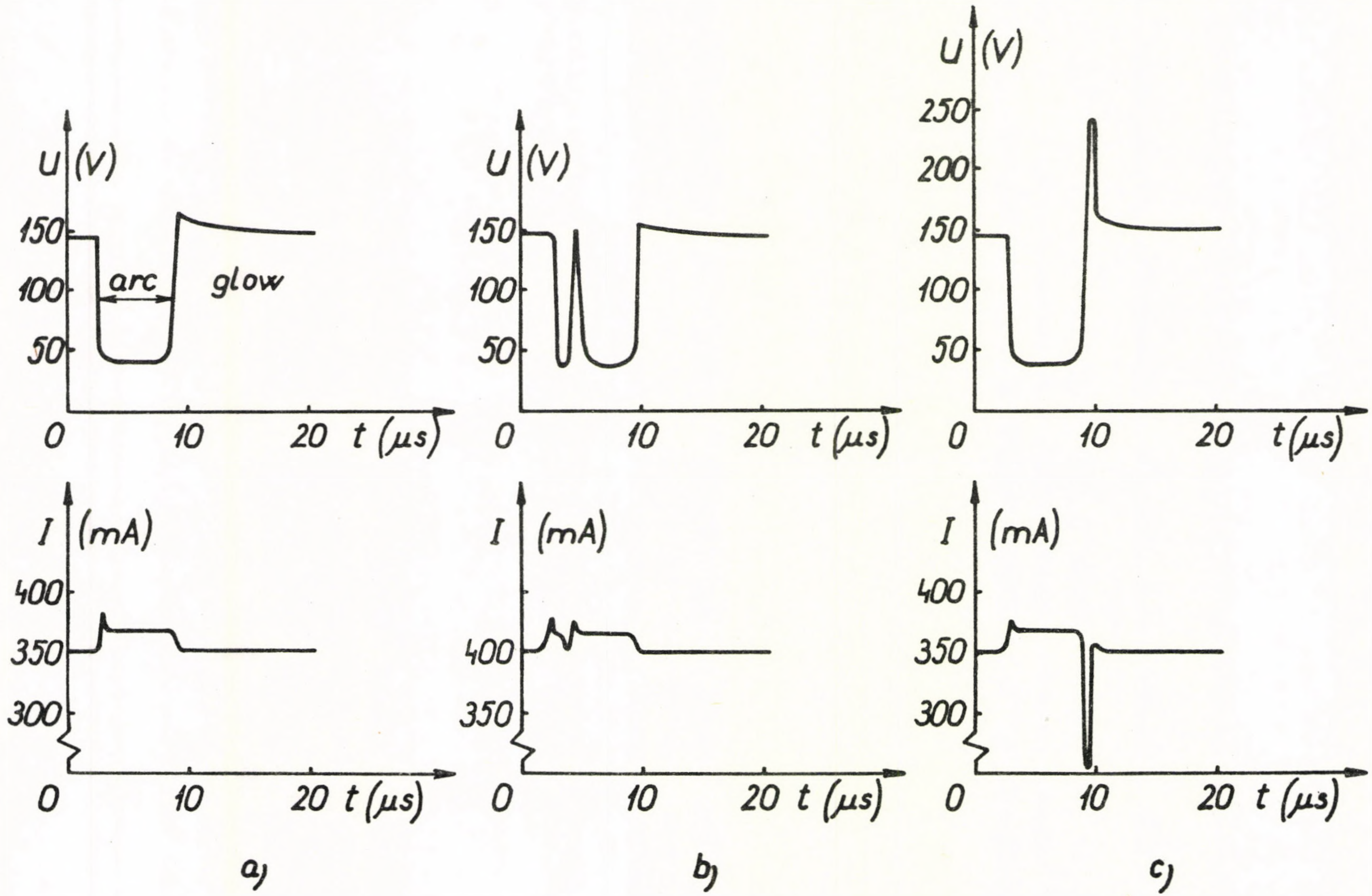

Fig. 2. Typical transitions from glow-to-arc and arc-to-glow measured by transient recorder in 22 mbar He. (a) "single" arc, (b) "double" arc, (c) the discharge stops after arc.

63.313

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Kroó Norbert
Szakmai lektor: Kertész Iván
Nyelvi lektor: Harvey Shenker
Gépelte: Balczer Györgyné
Példányszám: 330 Törzsszám: 82-627
Készült a KFKI sokszorosító üzemében
Felelős vezető: Nagy Károly
Budapest, 1982. december hó