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VERY HIGH POWER PLASMA SWITCHES. BASIC PLASMA PHYSICS AND SWITCH TECHNOLOGY

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VERY HIGH POWER PLASMA SWITCHES:

BASIC PLASMA PHYSICS AND SWITCH TECHNOLOGY

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ABSTRACT

A review of some high power switches recently developed for very high power technology is made with a special attention to the aspects of plasma physics involved in the mechanisms, which determine the limits of the possible switching parameters.

I. INTRODUCTION

The development of high voltage, high power technology has been very important during the last decades, for many high-power applications such as inertial confinement thermonuclear fusion, X-Ray lasers, X-Ray production from bremsthrahlung, neutron radiography, electromagnetic launchers, etc...

High power technology development requires fast switches to carry and interrupt large currents from a few kiloamperes to several megamperes, under large voltages from a few kilovolts to several megavolts. The physical and technological problems found in switches are different for closing switches and opening switches, as found in industrial applications of moderate power switches.

We present here a short review of several kinds of high power or very high power switches recently developed in many laboratories, both for closing and for opening switches. Many other devices exist, each of them having different characteristics which make each one of them of special interest for some particular applications. An exhaustive presentation is outside the scope of this paper and we will select here only a few devices which will permit us to focus our attention on the physical mechanisms involved in the switch operations, most of them based on plasma properties which determine the possible switch parameters.

II. HIGH POWER CLOSING SWITCHES

SPARK-GAP SWITCH

Spark-gap switches working in high pressure gas such as nitrogen and sulfurhexafluoride have been very widely used in high-power pulsed technology since the early seventies. They are known to permit very large currents (hundreds of kA to MA), to have a short current rise time of a few nanosecondes. This time corresponds to the time needed for the plasma channel to become a good electrical conductor. At the early time of the gas breakdown, the resistivity is very high due to electron neutral collisions in a weakly ionized gas. The avalanche breakdown produces a strong ionization of the plasma channel, the resistivity reduces dramatically to values associated with electron-ion collision frequency, or to anomalous resistivity of a turbulent collisionless plasma. The time required to produce this strong ionization is then the time during which the resistivity of the plasma channel keeps to high values, and is called the resistive phase time. It is given by the empirical relationship of J.C. Martin(1)

$$t_r = \frac{88\ d^{1/3}}{Z^{1/3}} \left(\frac{\rho}{\rho_0} \right)^{1/2} E^{-4/3}$$

where t_r is the resistive phase time in ns, d is the length of the spark gap in cm, E the electric field in units of 10 kV/cm, Z is the load impedance in Ohms, ρ/ρ_0 is the gas density relative to the density of air at temperature and pressure standard conditions. This relationship has proven to be accurate to within a factor 2 for a wide range of switch conditions.

The gas mixture is modified by the electrical discharge, and as the gas electrical strength is a sentitive function of impurities, successive discharges without changing the gas have very different parameters values; therefore, the gas has to be replaced between two successive shots, limiting severely the repetition rate to a few kiloHertz. Maximum speed of the fluid can be about 100 m/s, and the refilling time of the gas in the volume of the switch is then limited to a few tenths of millisecondes, giving a limit for the repetition rate of a few kHz. Figure 1 shows a possible geometry which permits a fast circulation of the gas between the electrodes. At Lawrence Livermore National Laboratory, a pulsed generator using a Blumlein is working with a repetition rate of about 10 kHz[2].

One of the main problem of the gas switch is the difficulty to trigger it with a very low jitter. The jitter strongly depends on the triggering voltage, and then using quite a large pulsed trigger generator is generally required. It is not rare to find devices in which the energy used to trigger the gas switches is of the same order than the total energy to be transfered through the device!...

A good solution for reducing the jitter in spark gap switches, is to trigger them using a UV laser pulse. While the jitter obtained in laser triggered spark-gap switches is typically larger than 15-20 ns for infrared or visible lasers, UV light around 0.25μm, permits a very fast ionization of SF_6 gas[3], and yields to jitter less than 1 ns. Such an UV pulse can be given by a KrF laser, or by a Neodynium laser with two successive frequency doubling KAP crystals for instance. These UV laser-triggered-spark gap switches have been demonstrated by Sandia National Laboratory to be efficient up to 2.8 Mev switches[3]. With laser pulse energy of about 10mJ, the jitter is less than 1 ns[3,4]

But even if the jitter can be reduced to very small values, the geometry of the spark gap switches does not permit very low inductances, and then the rate of current rise dI/dt will be limited. In large machines using spark gaps switches for energy transfer between two successive lines, a set of spark gaps is usually placed in parallel at the periphery of the inner line to reduce the total inductance.

During the past decades, the spark-gap switches has been the most used switches in high-power pulsed technology, but new needs came from the technology of low impedance machine with low voltage (a few tens to a few hundreds of kV) and very high current (a few hundreds of kA to a few megamperes), and from the technology of opening switches which permits power and voltage amplification.

PSEUDO-SPARK SWITCH

The pseudo-spark discharge is attributed to Christiansen and Schultheiss[5]. It is essentially a low pressure discharge between two metallic chambers, with two parallel-planar electrodes separated by a few millimeters in order to work on the left part of the Paschen curve which gives the breakdown conditions. The two electrodes have a central small hole which permits the particles to move through the holes to the chambers which form a hollow cathode on the cathode side, and an expanding chamber on the anode side, for the narrow electron beam formed on the axis. See Figure 2.

For applied voltages of several tens of kilovolts, the gas breakdown time is less than 20 ns and the maximum current can exceed several tens of kA. This switch has a good repetition rate capability.

Since 1979, many laboratories have studied this switch, with a large research effort in Europe[6] and development in Germany. In 1985, pseudo-spark switches were already replacing the classical hydrogen thyratrons for copper vapour lasers[7], and pseudo-spark switches are presently used in commutation of Blumlein for pulsed-high-power Nitrogen lasers which require a very fast rate of current rise. At CERN, a 400 kA generator has been built for 20 kJ pulses of 12 μs using four pseudospark placed on striplines with a jitter of 10 ns, for the plasma lens experiment[8]. To day, the typical parameters of such switches are:

voltage: 20 kV current: 10 kA
pulse duration: 20 ns repetition rate: 100 kHz
jitter:< 1 ns life time > 10^{10} shots
rate of current rise (dI/dt): 5 10^{11} A/s

SURFACE SWITCH

Surface switch using a discharge on the surface of a dielectric in vaccum or immersed in a gas are known since a long time[9,10]. We will discuss here only of the surface switch at atmospheric pressure, as they have much wider potential applications. Surface switches have low inductances nd could be, therefore, interesting for fast switching applications. The use of multichannel switch permits to increase the current to large values (hundreds of kA), and to decrease the total inductance. But during many years, these kinds of switch were considered as having a bad reliability of switching conditions, a difficult control of the channel number and a large jitter in operation when they are triggered.

More recent studies[11,12] have shown that triggering of a surface switch by cylindrical small electrodes provides a very good reliability if the electrodes are applied perpendicular to the dielectric surface of the switch with a constant pressure. See Figure 3. This permits to use surface switches even with very moderate voltage of 10-20 kV, with a linear current density of about 10 kA/cm; Currents in the MA range are possible with a large switch on a planar transmission line. As the current is carried along very thin weakly-ionized-gas channels produced on the surface of the dielectric, the electrical resistance is quite large during the few tens of nanosecondes. A large current rise is obtained only after a delay of about 40 ns, corresponding to the ionizing time of the plasma channel, and mainly determined by the triggering voltage. The physical mechanism involves first a gliding discharge on the surface of the dielectric, and from this electron cloud produced close to the surface, the production of a plasma channel via an avalanche effect which, during the first 10 ns, obeys the old (1944) Weizel and Rompe's law[13] which predicts that the plasma conductivity in the discharge channel is directly proportionnal to the internal energy of the discharge channel. The corresponding rate of growth of the current is maximum at a time t_m is given by[14]:

$$t_m = 9.5 \frac{p}{a\ E^2}$$

where "p" is the gas pressure, "a" a numerical factor, close to 1, independant of time which characterizes the nature of the gas, and E the electric field. The corresponding resistance of the channel varies like $\exp(-t\ aE^2/p)$ as found experimentally. For longer time, the Weizel-Rompe's law is no longer applicable and the resitive phase time is better given by the J.C. Martin's law.

III. HIGH POWER OPENING SWITCHES

If many kinds of closing switches exist at high power, the difficulty to open a circuit is increasing both with the applied voltage, as restrikes become highly probable, and with current, as a fast current variation will induce a large LdI/dt potential in the circuit. But opening switches are essential to some technological development, such as the inductive storage technology for instance[15,16]. The basic scheme of an inductive energy storage is shown in Figure 4. A large current source with generally a slow rate of current rise time is used, which can be a large capacitor bank or a high voltage pulse generator for instance. This generator is connected across an opening switch S_1 which works first as a short circuit and make the current to flow in the inductance L of the main circuit, in a long time depending on the inductance L and the bank capacitor C. For a capacitor bank, for instance, the time needed to reach the maximum current in the main circuit is a quarter of the period T, with $T = 2\pi\ (LC)^{1/2}$. When the current I is maximum, the closing switch S_2 is closed, connecting the inductor to the load Z while the opening switch S_1 opens. Due to the importance of the inductance L, the current in the main circuit cannot change without inducing a very large voltage LdI/dt.

Some plasma properties can be used to provide such high-power opening switches, and we examine here some of them.

REFLEX TRIODE OPENING SWITCH

The mechanism involved in a reflex triode can be used for producing an opening switch at very high power: A Reflex switch has been proposed by Physics International Company[17] based on this reflex mechanism: A high-power reflex triode is made of three electrodes, with a geometry similar to the familiar low power reflex discharge or Penning discharge: see Figure 5. An axial, uniform magnetic field of a few kG is applied parallel to the z axis, in order to limit the transverse motion of the electrons. The triode includes two identical cathodes K_1 and K_2, perpendicular to the z Axis, having the same negative potential, and a tranparent grounded anode A, placed parallel to and between the two cathodes. The electron produced on each of the two similar diodes are accelerated towards the anode and enter the other diode where they are decelerated, then oscillate around the anode where they loose some energy at each path, and are finally collected by the anode.

In a high power triode, the cathode K_2 can be a floating electrode, which will turn to be negatively biased at the same potential than K_1 by the first arriving electrons. The anode can be a thin foil transparent to the high energy electrons which transform the foil into a slowly expanding plasma. This anode plasma will be the source of an ion beam, mostly protons and graphite ions when a plastic foil is used as an anode. This ion current will reduce the electron space charge of the electron beam, permitting the electron current to grow. With the electron current increase, the ion current will be increased and the electron current will continue to increase as the electron space charge is reduced by the intense ion beam produced. Then, the total current flowing between the cathodes and the anode is much larger than the classical Child-Langmuir limit corresponding to the electron space charge alone.

This triode will work as an opening switch if the cathode K_2 is connected to ground: the electrons are no longer oscillating across the plasma anode foil, the reflex mechanism disappears, with the amplifying current mechanism discussed above. If the triode is placed in serie with a pulse generator and a load, when the cathode K_2 is grounded, the total current is reduced to the Child Langmuid limit, corresponding to large impedance increase of the circuit, quite similar to an opening circuit operation, even if the current does not completely vanishes.

PLASMA EROSION OPENING SWITCH

The plasma erosion switches research initiated by the work of Mandel and coworkers for suppression of the prepulse in high power diodes[18] at Sandia National Laboratory in 1977, and then a major effort has been done at the Naval Research Laboratory to demontrate the power multiplication[19] and application to inductive energy storage[20].

A plasma erosion switch consists of a vacuum-coaxial structure which connects a high power pulsed generator to a load. The coaxial structure is partially filled with the plasma injected radially with a velocity v_d from several plasma guns placed around the outer electrode. See Figure 6. The part of the coaxial structure located between the pulsed generator and the injected plasma cloud has an inductance L in which magnetic energy is stored while the current is delivered by the generator and returns to ground through the injected plasma which works first as a short circuit. The inner electrode carries a large current and will work as a magnetically insulated vacuum line, as the azimuthal magnetic field associated with this axial current will prevent the electrons to flow across the vacuum gap between the two coaxial electrodes. The plasma sources are fired a few microsecondes before the main pulsed generator in order to bridge the radial gap between the inner and the outer electrodes. Then the current grows in the first part of the PEOS structure, while the load is always in short circuit and receives almost no current. The main current flows radially in the injected plasma. Then the plasma disappears and opens the circuit after a few nanosecondes when the threshold current is reached.

The physics involved in a PEOS is very similar to the physics of a plasma-filled diode, in which a sheath is formed between the cathode and the plasma. Even if the detailed mechanisms are still a subject of controversies, most theories are based upon a model in which the current flows across the cathode-plasma sheath. Let us call I_g the current delivered by the generator and I_l the current flowing through the load.

Four phases have been described by the Naval Research Laboratory group[21]:

a) the conduction phase: At the early time, when the current I_g is rising from small values, the load current is nul and the total current is flowing through the plasma. The inner-cylindrical-electrode works as a cathode and emits an electron current I_e limited by space charge, while the plasma is the anode and emits an ion current I_i, and both currents are related by the bipolar flow classical ratio:

$$I_i \;/\; I_e = (\, Z\, m_e \;/\; m_i\,)^{1/2} \equiv \alpha$$

where Z is the ion charge, and m_e and m_i are respectively the mass of the electrons and of the ions. This small ion current controls the total current I which flows with an almost constant current density, but over an increasing distance up to the total plasma length l.

The total current I_g grows up to the threshold I_o which corresponds to the maximum available ion current:

$$I_o = S\, n_i\, e\, v_d \;/\; \alpha \qquad \text{with } S = 2\pi\, r\, l$$

where n_i is the ion density and r the cathode radius.

b) the erosion phase: When $I_g > I_o$, the ions are collected faster than they are replaced in the sheath, and the gap D between the cathode and the anode plasma grows. The current and voltage are related through the classical Child-Langmuir's law:

$$I_s = 2.33\ 10^{-10}\ S\ V_o^{3/2} \;/\; D^2$$

where V_o is the applied voltage.

c) the enhanced erosion phase: The current flowing in the central electrode produces an azimuthal magnetic field which bends the electrons. In the combined electric and magnetic fields, the electrons have "cycloid-like" trajectories resulting in an average drift along the axis as shown in Fig. 7c. The mechanism is here similar to the so-called parapotential theory of beam beam pinching which occurs for a critical current I_c of the order of the parapotential current[22] I_p:

$$I_p = \frac{I_o}{2} g \gamma_o [\gamma_o + (\gamma_o^2 - 1)^{1/2}]$$

where g is a geometrical factor of the order of r/D, and $I_o = 17$ kA. This axial electron motion increases the emitted ion current from the plasma[23].

d) When the current I_g exceeds this critical current, the electrons are confined along the cylindrical cathode and no longer cross the gap. The current is then only carried by the ions, and a fast plasma erosion yields to a rapid switch opening.

This plasma switches are to-day widely used for voltage and power multiplication[24,25],up to 24 MeV with 6 MA in PBFAII at Sandia National Laboratory. They are also introducing a new generation of very high power pulsed generators using inductive energy storage[16].

RAIL-GUN OPENING SWITCH

In inductive storage pulsed power system (see Fig. 4), a switch is required to close the circuit in order to store the energy into an inductor L, and then a commutator to connect the load in serie with the inductor, while an opening switch will disconnect the inductor from the main current source at the worst time, i.e. when the current is maximum. This put some very severe constraints to the opening switch.

The rail-gun switch interrupts a current by accelerating a preformed plasma out the end of a pair of conductors. The plasma can be produced for instance by an exploding annular metallic foil, the rail gun being made of a pair of coaxial conductors, as shown in Figure 8. In this particular case, the switch is used to power an imploding plasma load which is radially compressed to produce a dense and hot plasma.

A main capacitor bank is connected to the metallic foil trough the two rails of the rail-gun. The metallic foil is exploded, and due to JxB forces, is accelerated along the rails. Thus the switch closed time is determined by the acceleration time of the foil in the coaxial rail-gun. When the metallic plasma arrives at the end of the rails, the JxB forces cause the inner portion of the plasma to pinch, and the outer portion to blow out as an annular plasma puff, with an axial and a radial expansion. Both plasma portions motions contribute to a rapid rise in inductance. During the expansion of the outer portion of the plasma, the plasma density decreases and the plasma becomes collisionless, allowing the formation of an expanding sheath with increasing space-charge-limited impedance. A large dL/dt results in switch opening, which induces a large IdL/dt voltage on the load, in a very short time, i.e. with a large power.

Such a rail-gun opening switch has been built at Los Alamos National Laboratory[26] and yields to the following performance:

Maximum closed time: 15 μs
Minimum opening time: 720 ns (10-90%)
Current interrupted: 2.6 MA
Rate of current rise dI/dt: 3.5 10^{12} A/s
Inductive voltage at switching: 125 kV
Switch power dissipation 340 GW
Switch energy dissipation 120 kJ
Fractionnal energy dissipation 0.45
Peak bank power before switching: 11 GW
Power multiplication: 30

ELECTRON-BEAM CONTROLLED SWITCH

The electron-beam controlled switch is based upon the use of an electron beam to sustain a diffuse discharge in a high pressure gas. An illustration of such an opening switch is given in Figure 9. The gas resistivity is determined by a competition between ionization process and the various electron losses. The ionization is provided by the electron beam and the loss mechanisms include recombination and attachment which are dependant upon the gas characteristics, the pressure and the applied electric field, but to avoid the remanence of previous discharges, any arc discharge has to be avoided.

An analysis of energy transfer and switch physics has been made at the Naval Research Laboratory[27].

The physical model corresponds to an electron-beam which enters in a high pressure gas and produces a weak ionization. The ionization ratio $\alpha_i = n_e/n_o$ of the electron density n_e over the neutral density n_o being of the order of 10^{-5} only. The geometry is choosen to provide a good uniformity as any non-uniformity could yield to an uncontrolable gas breakdown. The size, energy beam and gas pressure are such that the electron range is slightly larger than the distance between the switch electrodes. The voltage is kept to low enough values to avoid gas breakdown. In this conditions, the gas resistivity is determined by the electron-neutral conditions. The used gas mixture is made of a nonattaching gas of neutral density n_o with a small fraction of attaching gas with density n_a. The fraction of the attaching gas is large enough to permit the attachment to dominate over the recombination, and thus yields to shorter "plasma lifetime" or characteristic time of electron density decay, when the electron beam is switched off. Then, the plasma resistivity can be written:

$$\eta = \frac{\alpha_i\ n_a}{e\ I_b\ \mu\ P}$$

where I_b is the carried current, $\mu = v/E$ the electron mobility, ratio of the average electron velocity v over the electric field E, and P the gas pressure.

The closing time is given by the ionization time by the electron beam which can be easily reduced to a few ns. The opening time is associated with the attachment process and is of the order of:

$$t = 1 / \alpha_i\ n_a$$

This kind of switch is not presently widely used, but it is presented here as one of the potential interesting devices. It can have a good repetition frequency, 10 kHz, and could easily switch several tens of kA under about 200 kV, with a conduction time of about 100 ns or 1 µs. The detail physics will depend on the exact nature and conditions of the gas mixture, as some well-known effects such as Ramsauer effect and energy storage in vibrationnal states of diatomic molecules can play some important role in the discharge history.

For such a switch, an electron beam current density of the order of 1 A/cm^2 could switch a main current density of about 100 A/cm^2.

FIGURE CAPTION

Fig.1 spark-gap switch with gas recycling

Fig.2 Basic scheme of a pseudo-spark discharge chamber.

Fig.3 Schematic of a triggered multichannel surface switch of planar-line.

Fig.4 Basic scheme of the switches used in a inductive energy storage pulsed power generator.

Fig.5 The basic geometry of a reflex triode

Fig.6 Plasma erosion opening switch setup on the diode of a high power pulsed generator.

Fig.7 The four phases of the NRL PEOS theory: a) conduction phase, b) erosion phase, c) enhanced erosion phase, d) magnetic insulation

Fig.8 Basic scheme of a rail-gun switch.

Fig.9 Scheme of an electron-beam controlled switch.

REFERENCES:

1 - J.C. Martin, AWRE Report No.,SSWA/JCM/1065/25, (1965)

2 - Reginato, "spark-gap with gas flow", Lawrence Livermore National Laboratory. (Reference to be completed before publication)

3 - J.R.Woodworth, R.G.Adams and C.A.Frost, UV-Laser Triggering of 2.8 Megavolt Gas Switches, IEEE Trans.Plasma.Sci.PS10, 257, (1982)

4 - J.M. Buzzi, B. Briou, H. Lamain, C. Rouillé, and E. Garate, "Thomson scattering of an Intense Electron Beam with Time and Space Resolution", Proceeds of 6th Int. Conf. on High-Power Particle Beams, 486, Ed C. Yamanaka, ILE Osaka, June 1986

5 - J. Christiansen and Ch. Schultheiss, "Production of High Current Particle Beams by Low Pressure Spark Discharges. Z.Phys.A290, 35, (1979)

6 - For instance: Institut Franco-Allemand de St Louis (France), Imperial College in London, University College of Swansea (England), University od Dublin (Ireland), Institut fur Kernphysik in Karlsruhe, Physikalisches Institut der Universitat Erlangen-Nurnberg, (Federal Republic of Germany)

7 - G. Mechtersheimer, R. Kohler, T. Lasser and R. Meyer, High Repetition Rate, Fast Current Rise, Pseudo-Spark Switch, J.Phys.E: Sci.Instrum., 19, 466, (1986).

8 - E. Boggash and H. Riege, A 400 kA Pulse Generator With Pseudo-Spark Switches, 5th Pulsed Power Conference, Arlington, June 1985.

9 - W.J. Sargent, R.S. Taylor, A.D. Adcock and K.E. Leopold, "Multi-channel Surface Spark Gaps", IEEE Transaction on Electron Devices, ED-25, 94, (1978)

10 - J.R. Burkes, J.P. Craig, M.O. Hagler, M. Kristiansen and W.M. Portnoy, A Review of High-Power Switch Technology, IEEE Trans.Electron Devices, ED-26, 1401, (1979)

11 - H.J. Doucet, W.D. Jones, S. Moustaïsis, H. Lamain, C. Rouillé, Proceedings of the 5th IEEE Pulsed Power Conference", M.F. Rose and P.J. Turchi Eds., 426, (1985) IEEE Cat N° 84-62399.

12 - H.J.Doucet, W.D.Jones, H.Lamain and C. Rouillé, "A Very-Low-Inductance Triggered Multichannel Surface Switch", to be published

13 - R. Rompe, W. Weizel. Z.Physik, 122, 636, (1944)

14 - G.A. Mesyats and G.S. Korshunov, "Formation of nanoseconds sparks in static breakdown of a gap", Sov.Phys-Techn.Phys., 13, 483, (1968)

15 - Karl.H. Schoenbach, M. Kristiansen and G. Schaefer, "A Review of Opening Switch Technology for Inductive Energy Storage", Proceed. IEEE 72(8), 1019, (1984).

16 - IEEE Transactions on Plasma Science, Special Issue on Fast Opening Vacuum Switch, PS-15, (1987)

17 - J.M. Creedon, L.J. Demeter, B. Ecker, C. Eichenberger, S. Glidden, H. Helava, and G.A. Proulx, J.Appl.Phys., 57, 1582, (1985)

18 - C.W. Mendel, Jr. and S.A. Goldstein, "A fast-Opening Switch for Use in REB Diode Experiments", J.Appl.Phys. 48, 1004, (1977)

19 - R.A. Meger et al, "Application of Plasma Erosion Switches to High Power Accelerators for Pulse Compression and Power Multiplication", in Proceed. 4th IEEE Pulsed Power Conf. Albuquerque, (1983).

20 - R.A. Meger, R.J. Commissio, G. Cooperstein and S.A. Goldstein, "Vacuum inductive store/pulse compression experiments on a High Power Accelerator Using Opening Switches", Appl.Phys.Lett. 42, 943, (1983)

21 - P.F. Ottinger, S.A. Goldstein and R.A. Meger, "Theoretical Modeling of the Plasma Erosion Opening Switch for Inductive Storage Applications", J.Appl.Phys. 56, 774, (1984)

22 - See for instance: N. Camarcat, H.J. Doucet and J.M. Buzzi, "High-Power Pulsed Electron Beam Transport", Advances in Electronics and Electron Physics, Supplement 13C, Very-High Density Beams, Ed. A.Septier, Academic Press, 1983.

23 - S.A. Golstein and R. Lee, "Ion-Induced Pinch and the Enhancement of Ion Current by Pinched Electron Flow in Relativistic diodes", Phys.Rev.Lett. 35, 1079, (1975).

24 - T.J.Renk and al., "Plasma-filled diode experiments on PBFA-II" Conference records of the IEEE Intern.Conf.on Plasma Science, 48, (1987) IEEE catalog No.87CH2451-3

- J.P. VanDevender et al., "Light Ion Research for Inertial Confinement Fusion at Sandia National Laboratory". Proceeds of 6th Int. Conf. on High-Power Particle Beams, 43, Ed C. Yamanaka, ILE Osaka, June 1986

25 - C. Bruno, J. Delvaux A. Nicolas & M. Roche. "Fast Opening Switch Application to Inductive Energy Storage and Theoretical Study of This Technology for 14-MeV Neutron Burst Production". Special issue on fast opening vacuum switches, IEEE Trans.on Plasma Sci. PS-15, dec 1987.

26 - D.R. Kania, L.A. Jones, E.L. Zimmermann, L.R. Veeser, and R.J. Trainor, "Experimental investigation of a magnetic gate as a multimegampere, vacuum opening switch", Appl.Phys.Lett.44(8), 741, (1984).

27 - R.J. Commisso, R.F. Fernsler, V.E. Scherrer and I.M. Vitkovitsky, "High-Power Electron-Beam controlled Switches", Rev.Sci.Instrum., 55, 1834, (1984)

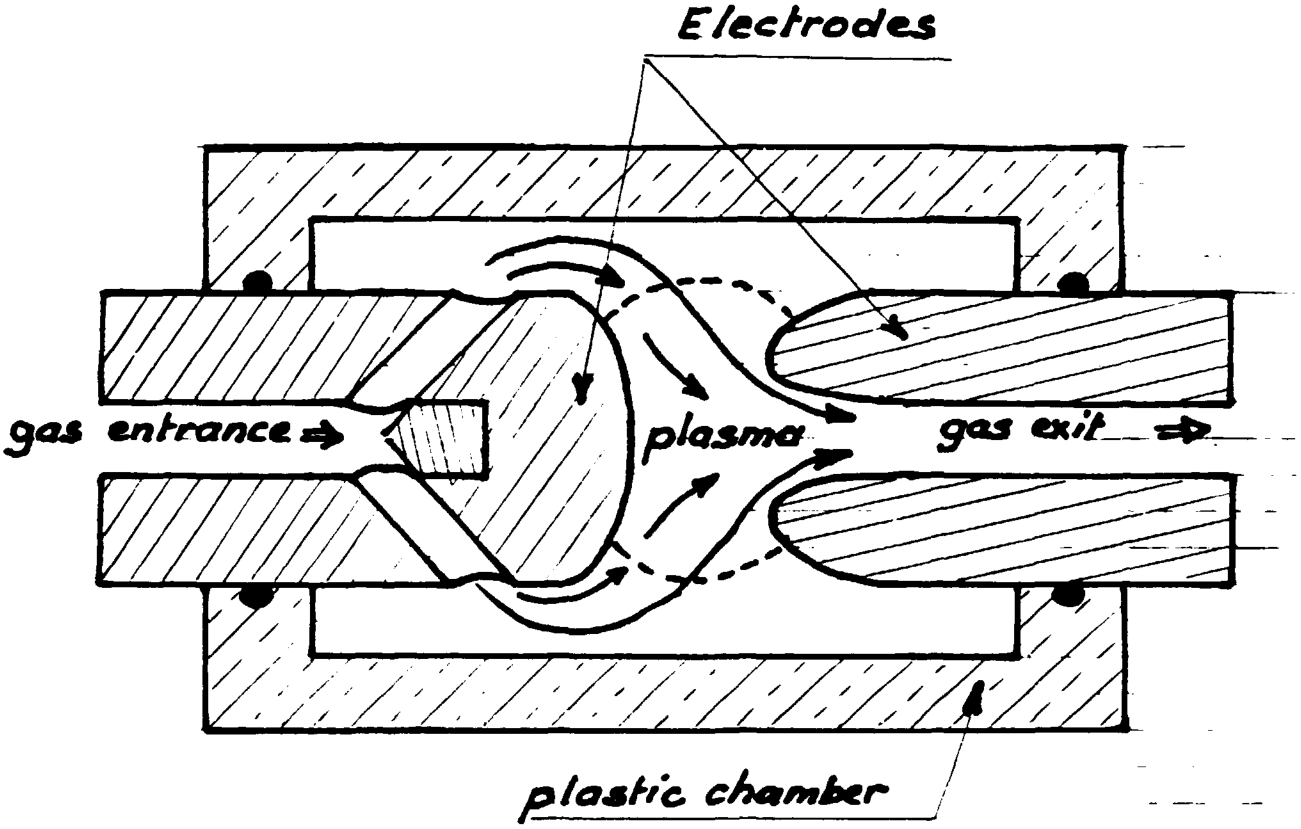

Figure 1

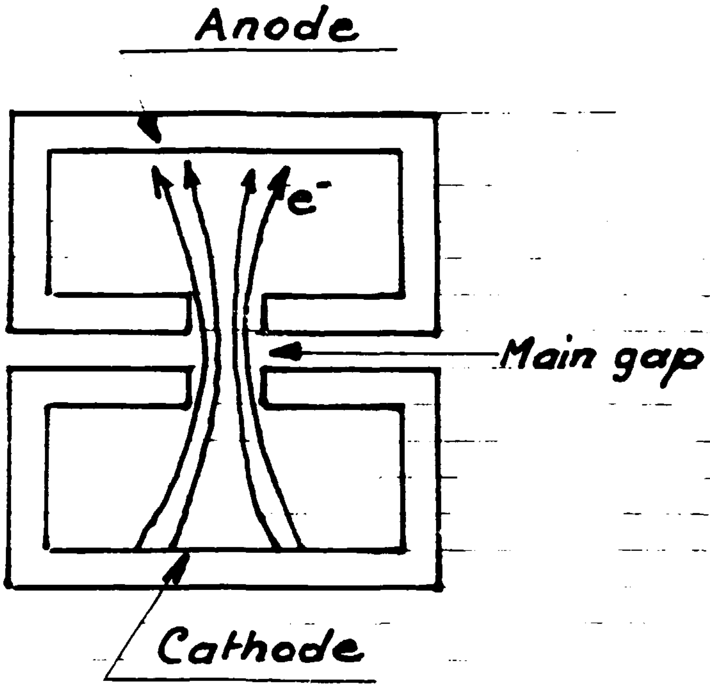

Figure 2

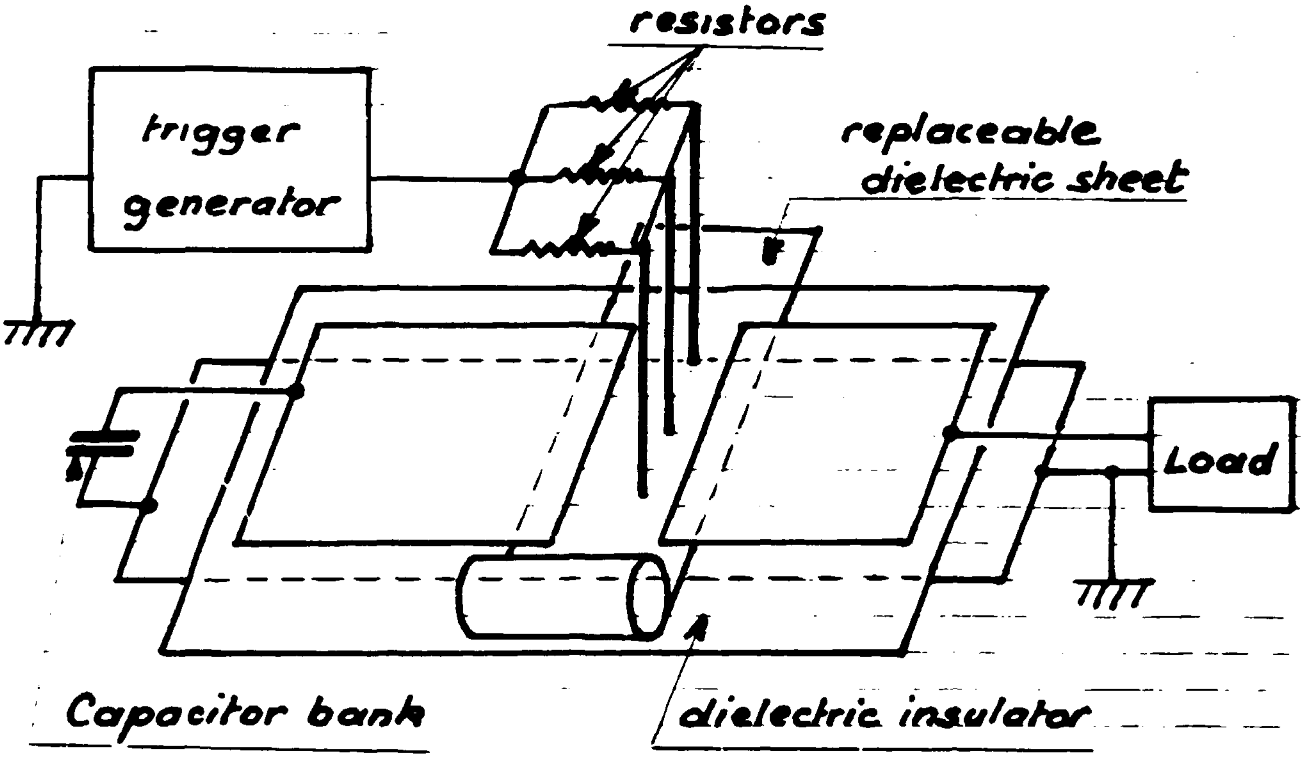
resistors
trigger generator
replaceable dielectric sheet
Load
Capacitor bank
dielectric insulator

Figure 3

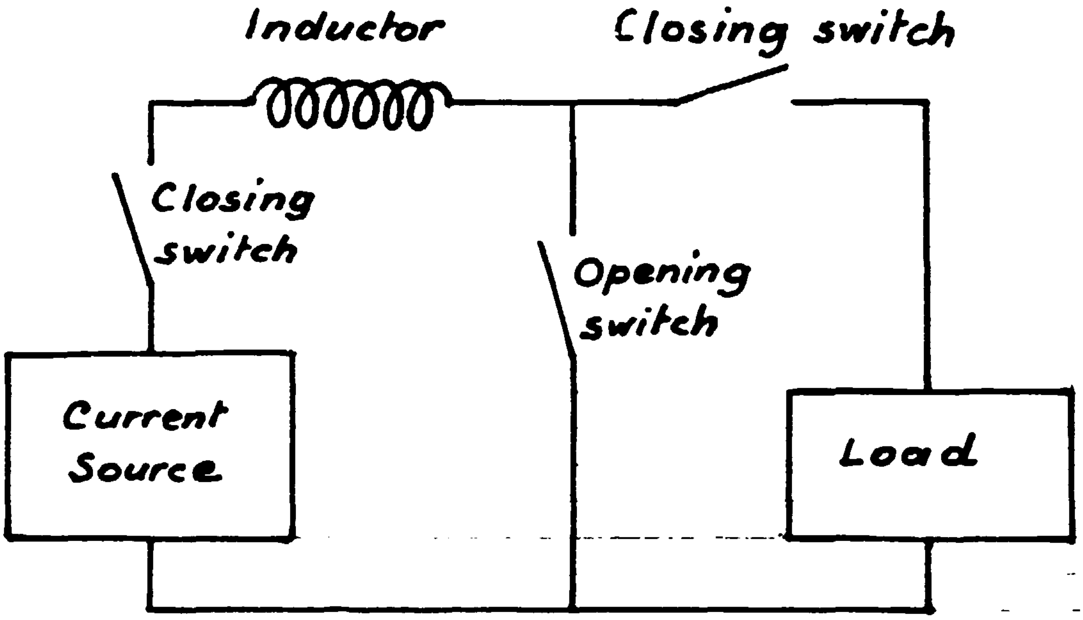
Inductor
Closing switch
Closing switch
Opening switch
Current Source
Load

Figure 4

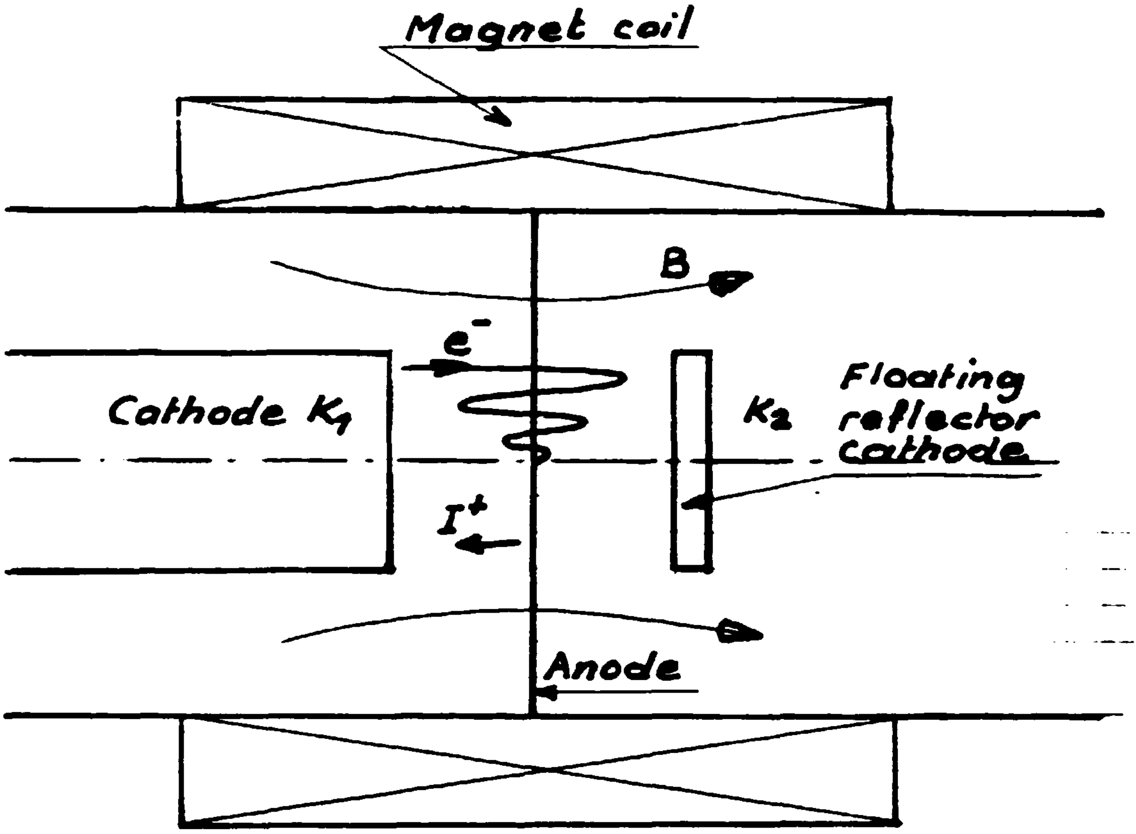
Magnet coil
B
e⁻
Cathode K1
K2
Floating reflector cathode
I⁺
Anode

Figure 5

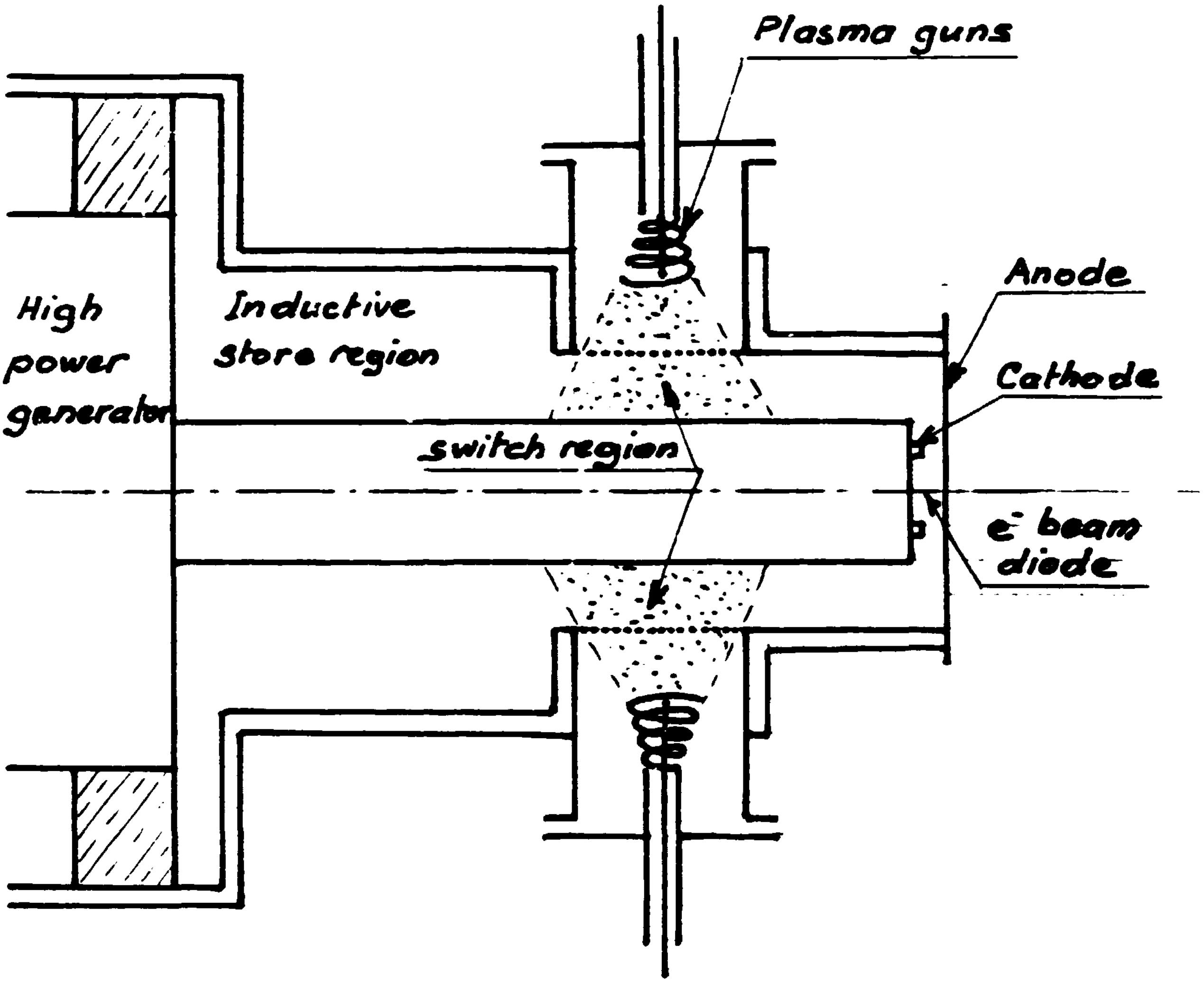
Plasma guns
Anode
Cathode
High power generator
Inductive store region
switch region
e⁻ beam diode

Figure 6

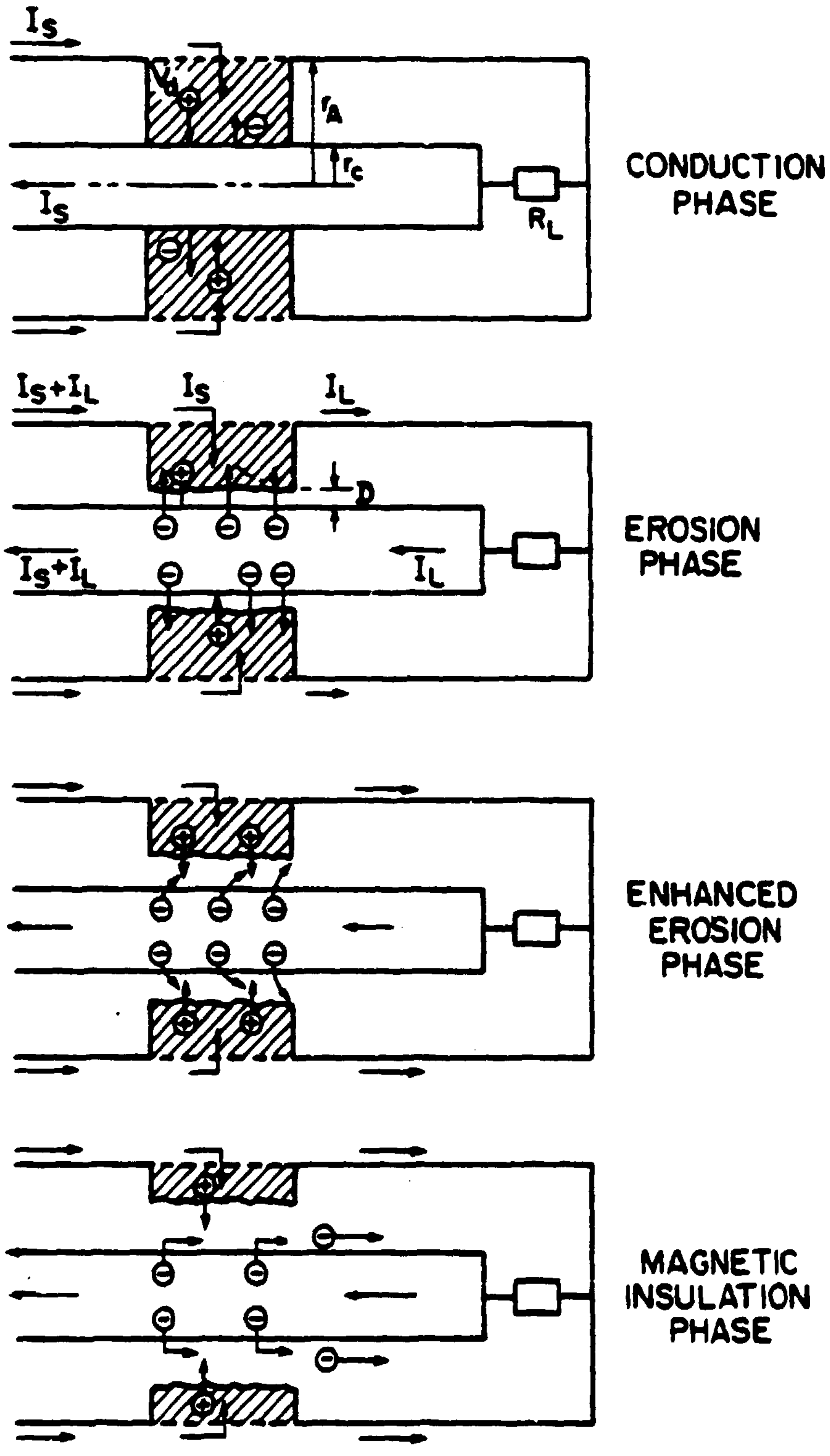
Is
rA
rc
Is
RL
CONDUCTION PHASE
Is+IL
Is
IL
D
Is+IL
IL
EROSION PHASE
ENHANCED EROSION PHASE
MAGNETIC INSULATION PHASE

Figure 7

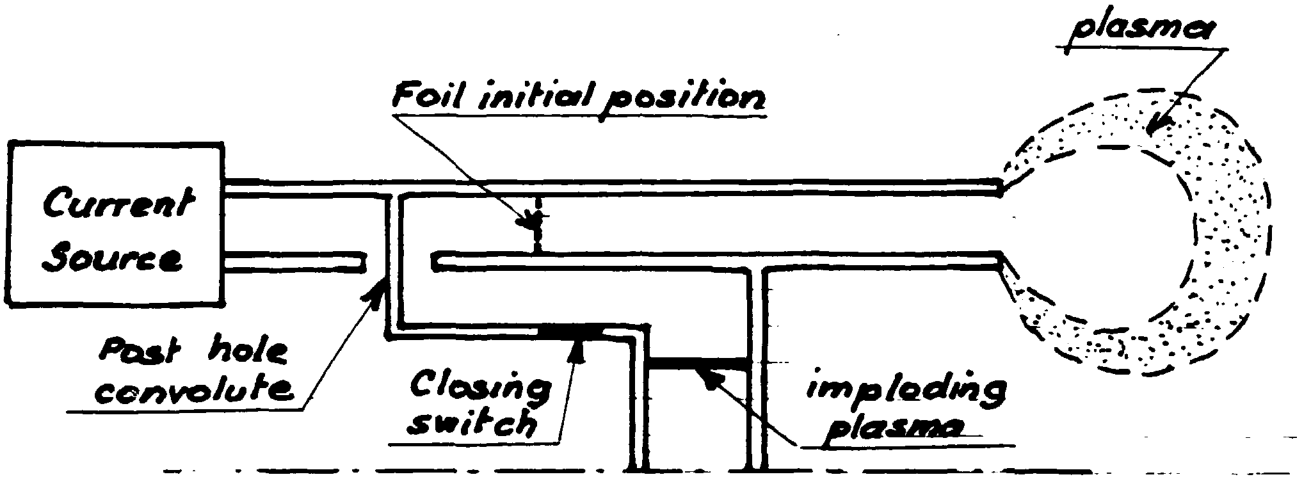
plasma
Foil initial position
Current Source
Post hole convolute
Closing switch
imploding plasma

Figure 8

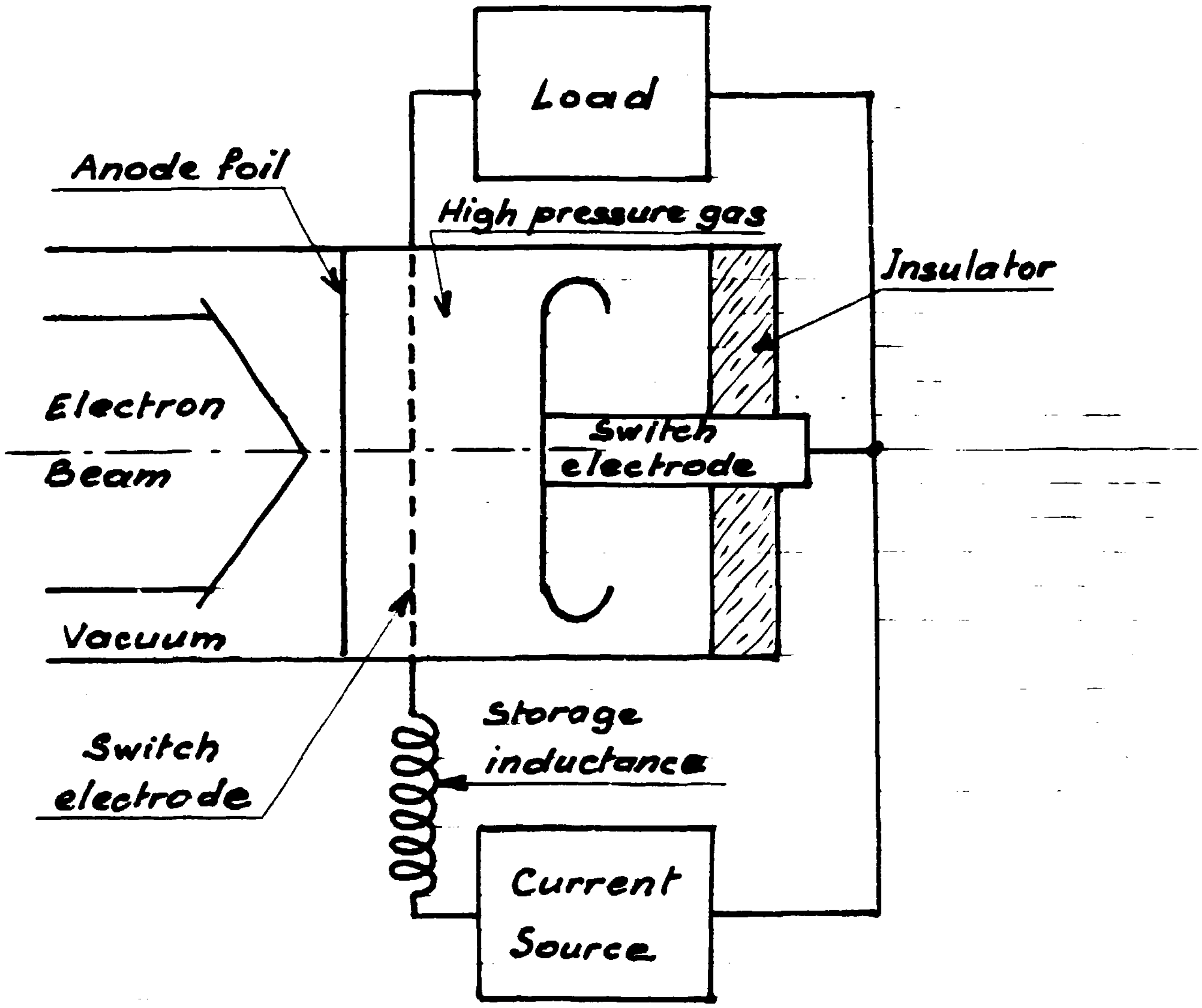
Load
Anode foil
High pressure gas
Insulator
Electron
Beam
Switch
electrode
Vacuum
Switch
electrode
Storage
inductance
Current
Source

Figure 9