

# Method for the Rapid Interruption of Large Electric Currents

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A method is described which promises the rapid interruption of large electric currents in very short times. The method is based upon the electrostatic interruption of a Brillouin flow in ultrahigh vacuum. The method may turn out to be very important for inductive energy storage devices.

The search for a switch which can interrupt large electric currents in very short times is recognized of great importance for inductive energy storage devices. We will describe here a switching technique which promises to interrupt currents of  $\sim 10^5$  Ampere in the time of  $\sim$ nanoseconds. The proposed device is intended for discharging the energy stored in a low inductance few turn cryogenic coil. It does not apply to superconducting coils, which inherently have long charging and discharging times.

The principle of the idea is explained in Fig. 1 showing a cylindrical vacuum tube in a cross section along its axis. The tube is located inside a magnetic field coil producing a strong axial magnetic field. The tube has a field emission cathode and a collector anode. Around the center of the tube is an auxiliary ring electrode, which is brought against the field emission cathode onto a large positive potential of several million volts. This can be done, for example, by connecting the ring electrode with a

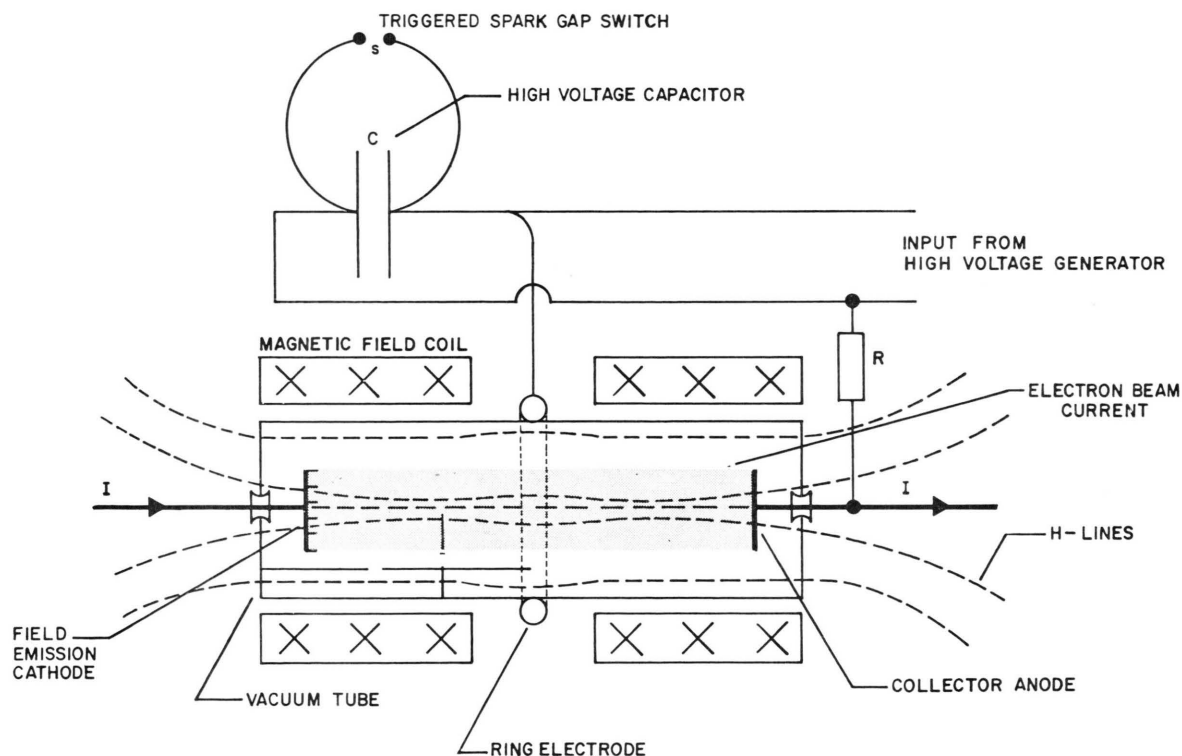


Fig. 1. The switch for rapidly interrupting a large current. C is a high voltage capacitor, s is an auxiliary triggered spark gap switch, R is a large resistor. (I is directed along the electron current.)

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Van De Graaff or with a Marx Blumlein line high voltage capacitor. This high voltage source is represented in Fig. 1 by the auxiliary capacitor C. After a high voltage is applied to the ring electrode a field emission current will start to develop. Normally, this field emission current would be discharged onto the ring electrode. If, however, a strong axial magnetic field is applied as shown in Fig. 1 the current can be prevented from flowing to the ring electrode if the following condition holds

$$E_r \ll H_z \quad (1)$$

where  $E_r$  is the radial electric field component and  $H_z$  the axial magnetic field strength applied externally, the electric field by the ring electrode and the magnetic field by the field coil, both measured in electrostatic units. This of course, is the necessary first condition for the principle of magnetic insulation<sup>1-3</sup>. The condition (1), which is the necessary condition for magnetic insulation has to be supplemented by a second sufficient condition for magnetic insulation explained below [see Eq. (16), and also Ref. 1 and 2].

If conditions (1) and (16) are satisfied the electron current will be confined radially. The electrons after being accelerated in the first half part of the tube towards its center at the position of the ring electrode are decelerated in the second half part of the tube and reach the collector anode with zero energy if the potential difference in between the cathode and anode is zero and if the processes of emission, acceleration and collection are without losses. However, this idealized condition is not expected to hold rigorously and a small potential difference in between the cathode and the anode has to be sustained in order to make up for these losses.

After the ring electrode has been connected to the high voltage source a current will flow from the cathode to the anode. This current serves as the charging current for the coil. If the coil is a low inductance few turn coil, for example, with a linear conductor dimension of  $\sim 10^2$  cm, the time for magnetizing the coil would be of the order of this length divided by the velocity of light, that is  $\sim 3 \times 10^{-9}$  sec. The field emission discharge is followed by a much slower plasma discharge flowing from the cathode to the anode. The plasma discharge results from the heating of the cathode material. If the separation distance in between the anode and cathode is of the order 10 cm and if the plasma cloud

moves with a velocity of  $\sim 10^6$  cm/sec (an estimate for tungsten at  $10^5$  °K) from the cathode to the anode it would reach the anode in about  $\sim 10^{-5}$  sec. After the plasma cloud has reached the anode the field emission current is replaced by a gas discharge. In this case the switch would remain short circuited and the current could not be interrupted in the proposed manner. It is therefore, intended, that the magnetizing of the coil shall take place in a time which is shorter than the time needed for the plasma cloud to short-circuit the switch. The estimated time of  $10^{-5}$  sec indicates that the coil must be charged in about  $\sim 10^{-6}$  sec. For coils with a longer charging time larger cathode anode separation distances could be used increasing the time for the plasma cloud to short-circuit the switch.

In order to interrupt this current a triggered spark gap switch  $s$  at the auxiliary capacitor C connected to the ring electrode has to be closed. This can be done in a time as short as  $10^{-9}$  sec. The voltage at the ring electrode will then drop in a time given by the  $1/4$  Thomson time (in electrostatic c. g. s. units)

$$\tau = \frac{\pi}{2c} (LC)^{1/2} \cong D/c \quad (2)$$

where  $L$  and  $C$  are the inductance and capacitance of the capacitor C and the ring electrode.  $D$  is the linear dimension of this system of conductors. If, for example,  $\tau = 1.6 \times 10^{-8}$  sec it follows that  $D = 4.8 \times 10^2$  cm = 4.8 meters, a value which can be easily realized by a Van De Graaff or Marx generator. After the voltage at the ring electrode has dropped, in the time given by Eq. (2) the field emission current will stop instantaneously and the electron current is suddenly interrupted. The same would be the case if the current from the cathode is produced by other processes, for example, by thermionic emission. In this case, after the voltage at the ring electrode has dropped off, the uncompensated electric space charge field would also immediately stop the current.

In Figure 1 the negative terminal of the high voltage source is grounded against the anode over a large resistor R in order to prevent the current from bypassing the vacuum tube.

The rapid interruption of the electron current is possible because of the very small inertia of the electronic charge carriers. Since in our case the electrons will be accelerated between the field emis-

sion electrode and the center of the tube to relativistic energies the acceleration time is given by

$$t_a \cong m c / e E_z, \quad (3)$$

where  $e$  and  $m$  are the electronic charge and mass and  $E_z$  the axial electric field component in electrostatic units. If the tube has a length  $2l$  and a radius  $R$  which is equal to the radius of the ring electrode and if a voltage  $V$  is applied to the ring electrode, the electric field  $E_z$  due to this applied voltage  $V$  near the field emission electrode is given by (in electrostatic units,  $V$  in volt)

$$E_z \cong V l / 300 (l^2 + R^2), \quad (4)$$

hence from (3)

$$t_a \cong 1.7 \times 10^{-5} (l^2 + R^2) / l V. \quad (5)$$

If, for example,  $V = 10^7$  volt and  $l = R = 10$  cm it follows  $t_a = 3.4 \times 10^{-11}$  sec, and for all practical purposes  $\tau \gg t_a$ .

The condition (1) for confined space charge flow (Brillouin flow) is necessary but not sufficient and has to be supplemented by a number of other restraints.

First, condition (1) does not include the self-electric and self-magnetic field of the beam current in the tube. But since the electrons attain relativistic energies in most parts of the tube along their trajectory, except near the cathode and collector anode, the azimuthal beam magnetic field  $H_\phi^B$  is almost completely compensated by the radial beam electric field  $E_r^B$ . Therefore, in all practical cases the externally applied axial magnetic field can be made sufficiently strong to over-compensate the repulsive forces of the beam self-electric field over the self-magnetic field. Since the electron energies near the emitter and collector electrodes are small, the externally applied magnetic field near the electrodes is not assisted by the self-magnetic beam field. To compensate the self-electric beam field one is therefore on the safe side if one simply requests that the externally applied magnetic field must be everywhere sufficiently strong to over-compensate both the radial electric field component resulting from the high voltage externally applied to the ring electrode and the radially oriented self-electric field of the beam.

Second, in order to avoid the diocotron instability the centrifugal force on the electrons resulting from the  $\mathbf{E} \times \mathbf{H}$  drift velocity must be small to the Lorentz force.

Third, for a space charge flow to be possible the axial electric field component of the externally applied electric field has to be strong enough to compensate the axial component of the space charge field resulting from the electron current.

We will now quantitatively formulate all the additional conditions as listed.

1) The radial self-electric field  $E_r^B$  of the current having a radius  $r < R$  is given by (in electrostatic c. g. s. units)

$$E_r^B = -2 \pi n e r, \quad (6)$$

where  $n$  is the electron number density in the beam current. Since the electron current obeys the relation ( $v$  electron drift velocity)

$$I = -\pi r^2 n e v \quad (7)$$

one has from (6) and (7)

$$E_r^B = 2 I / v r = \frac{c}{v} \frac{0.2 I}{r}, \quad (8)$$

the latter being valid if  $I$  is expressed in amp. The azimuthal magnetic beam field at the other hand is given by

$$H_\phi^B = 0.2 I / r \quad (9)$$

so that

$$H_\phi^B = (v/c) E_r^B$$

respectively

$$H_\phi^B < E_r^B, \quad \text{for } v < c. \quad (10)$$

For  $v \lesssim c$  one has

$$E_r^B \gtrsim 0.2 I / r. \quad (11)$$

Take for example  $r = 10$  cm,  $I = 10^5$  amp it follows  $E_r^B \cong 2 \times 10^3$  esu  $= 6 \times 10^5$  volt/cm.

The electric field at the emitter or collector electrode due to the externally applied voltage  $V$  is given by ( $E_r$  in electrostatic units,  $V$  in volt)

$$E_r \cong V R / 300 (l^2 + R^2). \quad (12)$$

Put for example  $R = l = 10$  cm and  $V = 10^7$  volt one then has  $E_r = 1.7 \times 10^3$  esu  $= 5 \times 10^5$  volt/cm.

In the center of the tube the radial component of the electric field is given by

$$E_r \cong \frac{1}{300} \frac{V}{R}. \quad (13)$$

For the given example this would yield  $E_r = 3.3 \times 10^3$  esu  $= 10^6$  volt/cm. The total electric field near the emitter or collector electrode is thus the sum of

the values given by Equation (11) and (12). Near the center of the tube the electric self-field is almost compensated by the selfmagnetic beam field so that the radial electric field strength is there determined by Eq. (13) alone. The condition (1) for confined space charge flow near the emitter or collector electrode has to be therefore refined as follows

$$\frac{1}{300} \frac{RV}{l^2 + R^2} + \frac{0.2I}{r} \ll H_z, \quad (14)$$

and in the center of the tube as follows

$$\frac{1}{300} \frac{V}{R} \ll H_z. \quad (15)$$

2) In order to avoid the diocotron instability the following relation must hold

$$m v_D^2 / r \ll e v_D H_z / c, \quad (16)$$

where

$$v_D = c E_r / H_z. \quad (17)$$

is the azimuthal electron drift velocity and where it was already assumed that  $E_r \ll H_z$ . Inequality (16) represents the second condition for magnetic insulation<sup>1, 2</sup>.

From Equation (16) and (17) one obtains

$$H_z^2 \gg \frac{m c^2}{e} \frac{E_r}{r}. \quad (18)$$

$E_r$  in Eq. (18) must, of course, include both the contribution resulting from the externally applied voltage as well as the beam field. The maximum contribution to  $E_r$  resulting from the externally applied field is given by Eq. (13) and the maximum

of the self-electric field of the beam is given by Eq. (11), hence by substituting in Eq. (18) the sum of both contributions and by putting  $r \cong R$  and  $v \cong c$  results in

$$\begin{aligned} H_z^2 &\gg \frac{m c^2}{e} \frac{1}{r} \left[ \frac{V}{300 R} + \frac{0.2 I}{r} \right] \\ &\cong 1.7 \times 10^3 \frac{1}{r} \left[ \frac{V}{300 R} + \frac{0.2 I}{r} \right]. \end{aligned} \quad (19)$$

3) In order to sustain a space charge flow axially an axial electric field  $E_z$  has to be applied. In our case  $E_z$  is given by Equation (4). The current  $I$  which can be sustained under the application of an external voltage and an electrode separation  $l$  is given by the space charge flow equation ( $I$  in amp,  $V$  in volt)

$$I = 7.3 \times 10^{-6} [l^2 / (l^2 + R^2)]^{3/2} (r/l)^2 V^{3/2}. \quad (20)$$

Or if a certain current  $I$  is required one can solve Eq. (20) for  $V$  giving

$$V = 2.7 \times 10^3 (l/r)^{4/3} [(l^2 + R^2)/l^2] I^{2/3}. \quad (21)$$

Take, for example,  $I = 10^5$  amp,  $l = r = 10$  cm it thus follows  $V = 1.1 \times 10^7$  volt.

We now check if the different conditions expressed by the inequalities (14), (15) and (19) are satisfied, for the following final set of parameters,  $V = 1.1 \times 10^7$  volt,  $I = 10^5$  amp,  $l = R \cong r = 10$  cm. We obtain from (14):  $H_z \gg 3800$  gauss, from (15):  $H_z \gg 3700$  gauss and from (19):  $H_z \gg 1000$  gauss. From these values it thus follows that a magnetic field of  $H_z \gtrsim 10^4$  gauss would suffice. Such a field can be produced without any difficulty.

<sup>1</sup> F. Winterberg, Phys. Rev. **174**, 212 [1968].

<sup>2</sup> F. Winterberg, Rev. Sci. Instrum. **43**, 814 [1972].

<sup>3</sup> R. Miller, N. Rostocker, and I. Nebenzahl, Bull. Amer. Phys. Soc. **17**, 1007 [1972].