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New Ways of Electron Emission for Power Switching and Electron Beam Generation

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Abstract

Strong electron emission from a plasma or a solid surface is the basis of many applications such as high-power switching or intense electron beam generation. The electron emission in pseudospark geometries, from the interior of a hollow cathode and from the outer cathode surface, is discussed. These types of emission are compared with other emission methods by taking into account the electron current density, the spatial and the energy distribution, the beam quality, and the mechanisms, which allow each process to be controlled. A combination of different types of emitters may be the best solution for efficient power switching and for intense electron beam production. As examples, ferroelectric emitters in pseudospark-like switches and in electron beam sources are described.¹

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1. INTRODUCTION

In many technical applications there is a steadily growing need for energy concentration in space and time. This is true not only in the field of high-energy particle accelerators but also for other high-power devices, such as lasers and free-electron lasers (FEL), inertial confinement fusion (ICF) drivers, material processing systems, and space applications. The increasing resistance against gigantism motivates the creation of very compact systems, which are energized for preferably only a limited time, during which they produce energetic output.

The problems arising from such systems are related mainly to the efficiency of conversion of primary energy into output energy. Low efficiency implies necessarily high losses, which in smaller and smaller volumes lead to material fatigue and destruction. A method or technology that does not provide very efficient energy conversion **cannot be considered for high-power devices**.

An example of such a method is the apparent weakness of high-pressure spark gaps in the field of high-frequency, high-power switching. Even at low repetition rates the performance is limited by severe erosion of the electrodes owing to the transition of the current from an narrow spark channel to the electrode surfaces. A considerable part of the switched energy is dissipated in the spark channel and on the areas of impact on the electrodes.

In the domain of particle accelerators, a high electric accelerating field $\vec{E}_{acc}$ is often claimed as the most important feature. A strong $\vec{E}_{acc}$ -field is, however, not sufficient to accelerate an **intense, high-brightness** beam to high energy. The primary energy has to be transferred **efficiently** from the accelerating structure to the beam. The high-intensity, high-energy plasma beat-wave accelerator is therefore an example of a technically impracticable device, because of the very poor overall energy conversion efficiency.

In this paper, selected practical methods of high current density power switching and of high-brightness electron beam generation are reviewed and proposed. There are certainly other schemes that give similar results. However, the methods and devices that are dealt with here have been partly proven in experiments and in technical operation. A vast potential for further performance upgrading should render them interesting for a large range of technical switching and electron beam applications.

2. HIGH-CURRENT EMISSION AND SWITCHING APPLICATIONS

In vacuum and gas switches, the charge transfer from one electrode to the other is mainly governed by the electrode surface properties and by the immediate interface with the interelectrode medium. Generally, even extremely high current densities can be obtained, e.g. 10^9 A/cm² have been measured in the hot spots of vacuum arc switches. The choice of current amplitude, current density, and discharge geometry for a specific high-power application is, however, challenging when the erosion of the electrode material should be kept low. The task of building an efficient, compact, low-inductance power switch, having a long lifetime, includes finding the optimum compromise between current and current density, discharge channel diameter, electrode surface area, and electrode material.

High-pressure spark gaps, thyratrons, ignitrons, and triggered vacuum-gap switches are nowadays the most widely used gas switches in high-power applications. Spark gaps are able to switch the highest peak powers and pulse energies, but at the expense of strong electrode erosion and complicated trigger systems [1]. Hence their use is restricted to low repetition rates. Careful design and choice of material

can nevertheless lead to impressively long lifetimes under hard conditions, as has been shown by the CERN spark gaps[2] that were developed for the fast ejection system of the Serphukov IHEP accelerator.²

Ignitrons are widely used in high-current switching applications, that are not too demanding in terms of switching precision and low inductance. They also suffer from a long recovery time and a decay of voltage hold-off capability under high pulse-energy conditions.

Thyratrons are probably the most common high-power precision gas switches used in power lasers, radar systems, pulsed magnet circuits, and many other pulsed power systems. Thyratrons can be operated at repetition rates above 10 kHz, voltages above 100 kV, and currents above 50 kA, however, not all at the same time and only for short pulse lengths. The current densities in thyratrons are generally limited to less than 10^3 A/cm² and high-current amplitudes are only feasible with large, heated current-emitting cathodes. The hold-off capabilities of thyratrons at high charging voltage are diminished by the steady presence of a d.c. discharge in the tube, which is necessary for the precise triggering.

In 1981 a new type of switch was developed at CERN in collaboration with the University of Erlangen [3]. These switches, based on the pseudospark phenomenon [4], combine some of the advantages of spark gaps, ignitrons, and thyratrons in a single unit [5]. Their special geometry permits the distribution of the current over a relatively large electrode surface area, although the discharge is not so homogeneous as in a thyratron. With a cold-cathode, current densities far beyond 10^4 A/cm² have been obtained in the CERN high-current switches [6] for the ACOI plasma lens test generator. This can be considered as a major progress in switching technology, since destructive effects are much smaller than in high-pressure spark gaps and only slightly worse than in thyratrons. Pseudospark switches can be triggered at least as precisely and efficiently as thyratrons and are therefore very suitable for high repetition rates (see Refs. [5] and [7]). Pseudospark switches also withstand current reversals up to 100% without any problems.

The operation of all high-power gas discharge switches, including vacuum gaps, requires a large number of initial charge carriers at the time of breakdown, and efficient physical electron emission mechanisms that tolerate the high current density during the conduction phase. Both requirements are generally fulfilled with electrons emitted from a cathode surface by one of the following four conventional processes, or by a combination of them:

- i) heating of a cathode surface (**thermionic emission**);
- ii) **secondary emission** from a cathode by bombardment with other particles (ions, neutrals);
- iii) extraction by a high electric field (**field emission**);
- iv) illumination with photons (**photoemission**).

All four mechanisms can be significantly enhanced by the proper choice of a cathode material with low work function. High-power gas switches are generally ignited by the processes of field emission and photoemission (laser triggering). Often the initial charge carriers are produced in the plasma of an auxiliary discharge [5]. In thyratrons, an auxiliary discharge is maintained all the time and is routed into the main discharge gap at the desired moment of breakdown.

² These spark gaps have been operated for 17 years in pulse generators of 80 kV, 8 kA, and 5 μ s with the same high-quality tungsten electrodes, and at current densities of 10^7 A/cm² in the spark channels!

The emission processes during the conduction phase of all high-power gas switches are more difficult to identify. Common to all types of switches is the presence of a discharge plasma in contact with the cathode surface. The slightly positively charged plasma fulfils three important functions for the current conduction:

- i) Whereas the bulk plasma is at constant potential, there is a sharp decay of potential across the Debye layer of width:

$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{e^2 n_e}}. \quad (1)$$

Here ϵ_0 is the dielectric constant, k is the Boltzmann constant, T_e is the electron temperature, e is the elementary charge, and n_e is the plasma density. For $n_e = 10^{17} \text{ 1/cm}^3$ and a plasma potential of $kT_e = 50 \text{ eV}$, we obtain an electric field of the order of MV/cm! This strong field is present just at the electrode surface, where it is most important for the emission.

- ii) Space-charge forces, which tend to push the electrons back to the emitting surface, are partly reduced when the electrons enter the plasma region.

The plasma is a rich source of ions which after being accelerated through the Debye layer, bombard the cathode surface for a short time and heat it up to the melting temperature. Hence thermionic emission, being a steeply rising function of temperature, will be substantially enhanced [8]. The current density of ions with mass m_i passing through the Debye layer towards the electrode is given by Bohm's equation (with $a \approx 1$):

$$j_i = a e n_e \sqrt{\frac{k T_e}{m_i}}, \quad (2)$$

which can greatly exceed the normal Langmuir-Child space-charge limit.

In all the gas switches under discussion, the combined thermionic and field emission, together with space-charge neutralization by the plasma and surface heating by ion bombardment, may result in an almost unlimited current density as observed in the hot spots of vacuum arcs. Such high densities can never be obtained in a pure vacuum.

Pseudospark switches profit from a favourable geometry, which leads to reduced electrode erosion while tolerating very high current densities ranging between those of spark gaps and thyatrons. Up to now, only the usual trigger methods of pseudospark switches [5] present certain disadvantages. The long-term performance of the so-called surface-discharge trigger is very poor. The charge injection trigger [9], on the other hand, is a source of premature discharge, as in thyatrons, especially in high-voltage switching applications. These disadvantages can be overcome with a new type of switch, which is triggered by a radically new method of electron emission.

Contrary to the four classical emission processes listed above, the proposed method [10] is based upon the fast reversal of the spontaneous polarization P_s of a ferroelectric sample. In this type of emission the reservoir of available charge on the sample surface is limited to maximum values of the order of $\Delta q / \Delta F = P_s = 0.5 \text{ C/m}^2$, where Δq is the charge, ΔF is the active surface area and P_s is the spontaneous polarization of the ferroelectric material. The amplitude of the emitted electron current density, $j_e = \Delta P_s / \Delta t$ is determined by the speed of the polarization reversal. The current amplitude is given by the area of the emitting surface, $I = j_e \times \Delta F$. The method is ideal for the preionization of large volumes

of arbitrary shape. If the polarization change ΔP , is induced quickly enough, the main gap of a high-power switch can be fired directly with the emitted electrons, without additional charge-carrier multiplication. A prototype switch of this type has been described elsewhere [11].

Here we propose a multistage high-voltage low-pressure gas switch with a hollow, cold cathode, which is triggered by a cold ferroelectric trigger in the absence of any d.c high-voltage potential (Fig. 1).

Figure 1: Scheme of a hollow cathode, low-pressure, two-stage, high-voltage switch triggered by an electron beam emitted from the surface of a ferroelectric sample (FE): $A_{1,2}$: anodes; $C_{1,2}$: cathodes; $I_{1,2,3,4}$: insulators; $S_{1,2}$: electrode screens; R: grading ring; T: electron beam stopper; AG: auxiliary grid; FE: ferroelectric disc; CR: contact ring; GE: grid electrode; V_A : potential of AG; V_R : pulse voltage on back of the FE-sample; V_G : potential on GE.

The switch geometry resembles that of a pseudospark structure, but in principle the electron beam cross-section can be shaped into any desired form following the layout of the electrodes, e.g. into multiple beam bundles with multihole electrodes, or into hollow beams of large internal diameter with ring-shaped electrodes. In fact, a charge multiplication process, such as in a pseudospark discharge, is not required for breakdown initialization owing to the abundant electron emission from the ferroelectric trigger FE. The e^- beam triggers all stages of the switch simultaneously, thus reducing breakdown delay and current rise-time. The FE sample (generally made from a ceramic lead-lanthanum-zirconium-titanate, known as PLZT, is subjected to a fast HV pulse from a transistor-switched electronic power circuit. The sample electrode facing the HV stages is perforated to allow for e^- emission from the bare surface. The auxiliary grid AG shown in Fig. 1 can be used either for investigating the emitted e^- beam or for increasing the hold-off voltage of the main switch by applying a potential of a few hundred volts [3]. In this case, some gas amplification will further enhance the trigger-beam intensity. The main switch stages must be graded potential-wise as for thyratrons.

We can summarize the advantages of the new HV switch as follows;

- i) The ferroelectric trigger system does not contain any heated element (cold electrodes, ceramic insulators and ferroelectrics) or any permanent discharge.
- ii) The e^- trigger beam is so dense that gas amplification is not needed and direct firing of the main switch becomes possible. The switching delay is of the order of several tens of nanoseconds. In [11] less than 5 nsec jitter were measured with a non-optimized FE trigger system in combination with a pseudospark switch structure. Delay and jitter are determined mainly by the characteristics of the electronic trigger circuit, by the distance of the FE sample from the main gap, and by the type of ferroelectric material.
- iii) Unlike surface discharge triggers with organic glide-spark insulators, the ferroelectric emitter does not develop organic vapours or other contaminating products. The auxiliary grid AG protects the emitting FE surface from contamination by deposits coming from the main discharge region and against intensive contact with the discharge plasma.
- iv) The main switch is built with a cold cathode. Owing to the absence of hot elements and of permanent glow discharges inside the switch, a better hold-off voltage can be achieved than with thyratrons. The excellent trigger efficiency allows the switch to be run far away from the breakdown voltage so that, compared with high-pressure spark gaps, a gain in prefiring safety can be obtained.
- v) As in pseudospark switches, high main-current densities of 10^4 to 10^5 A/cm² and currents up to 100 kA can be combined with low electrode erosion rates.
- vi) The strong e^- beam passing through the main switch after breakdown can be dumped on a thoriated-tungsten target or on a LaB₆ target. The e^- beam can also be diffused inside the hollow anode by means of an insulating ceramic target.

The full use of the favourable features listed above should make it possible to build compact, low-inductance, single-unit switches for voltages above 100 kV and 100 kA.

3. ELECTRON EMISSION AND BEAM SOURCES

In high-power switching, it is the current density that is of main interest, and it is of less importance, how the beam current is emitted from the surface and transferred into the adjacent gap medium. However, the realization of a particle beam source depends strongly on the way in which the beam is emitted and then transported to its destination. Generally, several problems have to be solved, when the electrons produced by any of the five emission methods described in the previous chapter, shall be transformed into a technically manageable beam.

In most of today's e^- beam sources, electrons are injected thermionically into vacuum with the assistance of a high d.c. or r.f. electric field. Recently, laser-illuminated photocathodes have been successfully implemented in direct combination with r.f. field extraction into vacuum [12]. With thermionic sources, hardly more than 10 A/cm^2 beam-current density can be extracted from an emitter, whereas with laser photocathode sources more than 500 A/cm^2 have been achieved on a picosecond time-scale. Beam pulse-shaping in time and geometry is the big advantage of this method. However, when injecting into vacuum, both methods have to fight with space-charge forces whenever very high beam-current densities are envisaged. The Langmuir-Child law is a natural limit for the emitted current density, and the extraction field cannot be infinitely increased. The thermal material resistance is, on the other hand, the limiting factor for heating the emitter electrically or by means of an intense laser pulse. Hence the classical ways of raising the emitted current density -- i.e. by increasing the surface temperature, and/or the laser intensity, and the extraction field strength -- become practically inefficient when one requires emitted beam-current densities that are one or more orders of magnitude higher than are feasible today.

The method of e^- emission is also a decisive factor for the **beam quality** of the source. For high-energy accelerators and FELs, low normalized emittance and high brightness are essential beam parameters. The normalized emittance ε_n is derived from the r.m.s. emittance ε [13] by

$$\varepsilon_n = \beta \gamma \varepsilon, \quad (3)$$

where β is the ratio of electron velocity v_e to the velocity c of light, and $\gamma = (1 - \beta^2)^{-1/2}$. The normalized emittance of an emitter of absolute surface temperature T and of radius r_{em} can be written as

$$\varepsilon_n = 2\pi r_{em} \sqrt{\frac{kT}{m_0 c^2}}, \quad (4)$$

with m_0 being the electron rest mass and measured in units of mrad. The normalized emittance ε_n can also be expressed in terms of current I and current density j_e , with $I = \pi r_{em}^2 j_e$, as

$$\varepsilon_n = 2 \sqrt{\frac{\pi k T I}{m_0 c^2 j_e}} \quad (5)$$

with I in A and j_e in A/cm^2 .³

The normalized brightness B_n of the beam is given by

³ Note, by this definition ε_n contains π .

$$B_n = \frac{I}{\varepsilon_n^2}. \quad (6)$$

For a given current requirement, the low emittance and high brightness are obtained with the **high current density and low temperature** of the emitting medium. The equations for emittance and brightness are only theoretical limits. In practice, one generally achieves performances that are worse by one or two orders of magnitude. A thermionic emitter of 1100°K surface temperature ($kT = 0.1$ eV) is able to emit up to 20 A/cm². For a total current of 100 A it should, theoretically, produce a beam with a minimum emittance of $\varepsilon_n = 3.5 \times 10^{-5}$ mrad and at best a brightness of $B_n = 10^{11}$ A/(mrad)².

In photocathodes the equivalent temperature is considerably higher than in thermionic emitters. However, much higher current densities of several hundred A/cm² have been obtained by laser illumination, and with a special low-work-function photocathode material the effective surface temperature can also be shifted below $kT = 1$ eV. With a current of 100 A, a photon energy of $kT = 0.5$ eV, and a current density of 500 A/cm², a normalized emittance of 1.6×10^{-5} mrad and a brightness of 4×10^{11} A/(mrad)² are, theoretically, feasible.

The electron emission from ferroelectrics into vacuum has been studied in PLZT ceramics with HfV-pulse polarization reversal [14]. In a rather slow 50 Ω cable pulser, emitted current densities greater than 10 A/cm² have been measured. Taking into account again a total current of 100 A and $kT = 0.025$ eV (room temperature!), the emittance from a ferroelectric surface is calculated to be 2.5×10^{-5} mrad and the brightness as 1.6×10^{11} A/(mrad)². This is better than a thermionic emitter, but worse than a laser-illuminated photoemitter. With faster and more powerful electronic pulsers, considerably faster polarization reversal -- and consequently higher current densities -- can be expected from ferroelectrics.

In vacuum all emitters suffer from strong space-charge fields induced by the electrons that have just left the surface, and from the irregularities of the emitting surface, which lead to strong field distortions near the surface. Both effects are responsible for the emittance degradation and the blow-up of the ejected beam, even when strong extraction fields are applied. Magnetic focusing could counteract the beam blow-up, but it is inefficient owing to the small velocity of the electrons near the surface.

Now we may ask why electron beam sources should not profit from the favourable plasma surface interaction, as in the case of high-power switches. First we will discuss some data on electron emission from a plasma, using the example of pseudospark electron-beam sources, which have been studied for several years. A striking feature is the current density of these sources, which beat all other emitters by orders of magnitude [4]. In Ref. [15] measurements of total current and of beam diameter were used to deduce the emittance data. It should be pointed out that the pseudospark beam is very complex, since the current density, the beam diameter, and the kinetic energy of the electrons vary strongly along the beam pulse. Hence, also the emittance and the brightness are not constant. Recently, the **average** emittance and brightness of a pseudospark beam have been measured experimentally to be 5×10^{-5} mrad and 2×10^{11} A/(mrad)², respectively [16]. Parts of the beam certainly have smaller emittances. With a beam current density of 10⁵ A/cm², a total current $I = 100$ A as above, and a plasma temperature of $kT = 50$ eV, we can calculate an emittance of 1.2×10^{-5} mrad and a brightness of 7×10^{11} . These data depend strongly on the estimated plasma temperature. With a 10 eV plasma, 5×10^{-6} mrad and 4×10^{12} A/(mrad)² become possible.

Interesting measurements have also been done with ferroelectrics in a plasma environment [17]. A plasma was produced by a pseudospark electron beam. A second beam was generated by polarization reversal from a ferroelectric sample and then sent directly into the plasma. The second beam travelled for 20 cm through the plasma before being partially ejected into vacuum. Beam-current densities of more than 1000 A/cm² have been measured. Assuming again a total current of 100 A for such an

emitter, which is at room temperature, an emittance of 2.5×10^{-6} mrad and a brightness of 1.6×10^{13} can be calculated. There are good chances that the current density emitted into a plasma from a ferro-electric sample can be further increased by choosing faster emitting material and polarization reversal circuits. One can then expect theoretically an emittance below 10^{-6} mrad and a brightness above 10^{14} A/(mrad)².

The significantly higher emission into the plasma can -- like the current emission in high-power switches -- be explained by the action of the strong electric field in the Debye layer just on the surface of the emitter. After having left the emitter surface, the beam is much less subject to space-charge forces and emittance blow-up than a beam emitted into vacuum. Even if the plasma density is less than the beam density, there is a strong reduction of the beam space-charge field. It has been shown in many experiments that the beam can travel rather long distances without being focused through a plasma, or even, with some ionization losses, through a low-pressure gas.

Whilst electron emission and transport are relatively easy to handle in a plasma, acceleration is a more difficult problem. The plasma tends to cancel the radial electric field E_r of the beam by a space-charge neutralization factor f_e ,

$$E_r = 2\pi en_0 r_b (1 - f_e), \quad (7)$$

and the magnetic self-field B_θ by a current neutralization factor f_m ,

$$B_\theta = 2\pi en_0 r_b \beta (1 - f_m), \quad (8)$$

where n_0 is the plasma density and r_b is the beam radius. Then the beam envelope can be approximately described by [18]

$$\frac{d}{dt} r_b - \frac{2el}{\gamma m_0 \beta c r_b} [1 - f_e - \beta^2 (1 - f_m)] = 0. \quad (9)$$

The plasma screening not only reduces the beam self-fields but also prevents external accelerating fields from penetrating through the plasma towards the beam. The only possible way around this obstacle is to decrease the plasma density to below the beam density until the penetration depth of the external field exceeds the beam diameter r_b ('under-dense plasma'). Induction acceleration with nanosecond pulses seems the best way of raising the kinetic energy of plasma-embedded beams.

The use of an under-dense plasma may force the reintroduction of a focusing field. A simple, passive, electrostatic focusing method has been tested on a pseudospark beam by H. Gundel as reported in Ref. [19]. A pseudospark electron beam was injected into an insulator tube of 2 mm inner diameter and 70 cm length. The mean beam energy was 35 keV. The beam current was measured by two beam-current transformers, one at the entrance and one at the exit of the tube (Fig. 2). The radial focusing was so strong that a significant longitudinal distortion of the beam was observed; the front electrons were accelerated and the trailing ones decelerated to a few hundred eV. The resulting, mean current neutralization factor f_m was about 70%. The violent compression effect on the beam electrons, which is caused by the electrons expelled from the plasma towards the insulator wall, will be smoother if the beam is short and longitudinally more uniform, and if the tube is filled with plasma before injection.

A proper choice of tube diameter, plasma diameter, and plasma density will mean that the strength of focusing and the beam distortion in the expansion direction can be controlled, while offer-

ing the possibility of simultaneous induction acceleration.

Figure 2: Electron beam current a) in front of and b) behind an insulating tube, which acts as strong, transverse focusing element while increasing the energy spread of the beam. Each trace contains five pulses: a) 5 A/V, 10 A peak current; b) 5 A/V, 4 A peak current

A plasma electron beam source is now proposed that combines all the beneficial effects described above, in order to produce beam intensities that are an order of magnitude better than those generated by existing sources. At the same time, beam emittances that are much lower than those from conventional sources may be achieved. Figure 3 shows a source consisting of a pseudospark section, which generates an e^- beam for plasma production in the chamber and along the adjacent beam transfer tube (insulator). During the breakdown phase of the pseudospark chamber, a ferroelectric emitter is activated by rapid polarization reversal, and a short e^- pulse is emitted into the pseudospark plasma, as described in Ref. [17]. It is immediately focused by the insulators and the floating electrodes of the chamber, and later by a tapered tube along which the density of the plasma decreases owing to differential pumping. After acceleration to relativistic energy by several induction units the beam is injected into vacuum through a small hole. The beam energy is now sufficiently sensible to magnetic focusing and is ready for the application of classical bunch compression and r.f. accelerating techniques. The decoupling of the source and the conventional accelerator part allows also efficient synchronization of the beam pulse with the r.f. phase.

It is not absolutely necessary to have a ferroelectric medium as emitter in this particular source; it is just convenient. Any other method that generates short, intense charge pulses at the pseudospark plasma-emitter interface may give good results. Short beam pulses have been obtained with a simple capacitor discharge on the rear side of the pseudospark chamber. If plasma-resistant photocathodes can be found, a laser could be used for beam and plasma production. The pseudospark is just a simple and cheap way of doing the same job.

1: capacitor	15: d.c. charging voltage HV_1
2: RE (rear electrode of FE)	16: d.c. charging voltage HV_2
3: FE (ferroelectric sample)	17: d.c. charging voltage HV_3
4: ceramic focusing tubes	($HV_2 < HV_3 < HV_1$)
5: cathode of pseudospark chamber	18: storage capacitor
6: trigger electrode	19: fast transistor switch
7: focusing plasma electrons	20: coupling transformer
8: high-density plasma	21: trigger pulse
9: induction field coils	22: grid electrode GE
10: solenoid coils	23: hollow cathode plasma
11: bunch compression, rf-feedback	24: electron beams
12: rf-cavity	25: multidisc pseudospark chamber
13: exit hole to vacuum	26: anode
14: vacuum region	27: PFN for induction acceleration

Figure 3: Schema of an e^- beam source with e^- emission from a ferroelectric surface with a differentially pumped plasma tube, with strong, passive electrostatic focusing, with inductive acceleration, and with transmission into vacuum

4. CONCLUSIONS

The plasma-electrode interaction is the basis for high-current density generation in high-power gas switches. The combination of the high extraction field in the Debye layer with the heating of the electrode surface by ion bombardment is the reason for the abundant currents observed since a long time in most types of gas switches. The new type of high-voltage switch triggered by a ferroelectric trigger, which has been described here, does not contain any hot element, discharge, or high d.c. potential. Such switches may be used in future in the fast-pulsed beam deflection and beam-dump systems of high-energy particle accelerators as well as for the modulators of radiofrequency and radar systems. They should be able to commute substantially higher power at higher current and voltage levels than can the conventional thyristors.

The beneficial effects of a plasma are also interesting for intense electron beam sources. Apart from very high beam-current densities, one can expect excellent beam quality in terms of emittance and brightness. An easy-to-build electron beam source is described. The behaviour of most of its elements has been studied successfully in separate experiments. The whole assembly is believed to give one order of magnitude higher beam current density and a substantially lower emittance than can be achieved with conventional sources. The source may be used as an injector for linear accelerators, for FELs, for gas-laser preionisation, for electron-beam-controlled switches, and for electron guns applied to machining, and to X-ray or microwave generation.

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