INVESTIGATIONS OF INTENSE PULSED ELECTRON BEAMS FROM PSEUDO - SPARK DISCHARGES

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Abstract

A low-pressure gas discharge is presented as a source of intense pulsed electron beams. The so-called pseudo-spark discharge emits a short-duration pinched electron beam during the breakdown phase. At a voltage of typically 40 kV, an appreciable part of the total discharge current appears as the electron beam current of typically 10 nsec in duration.

Introduction

Low-pressure gas discharges normally are characterized by the formation of run-away electrons during the breakdown phase of the discharge. The optimization of electron production and beam formation in low-pressure gas discharges led to the development of a discharge geometry as shown in fig. 1) /1/. A pair of plane parallel electrodes with circular holes on a common symmetry axis is held in place by an insulator ring.

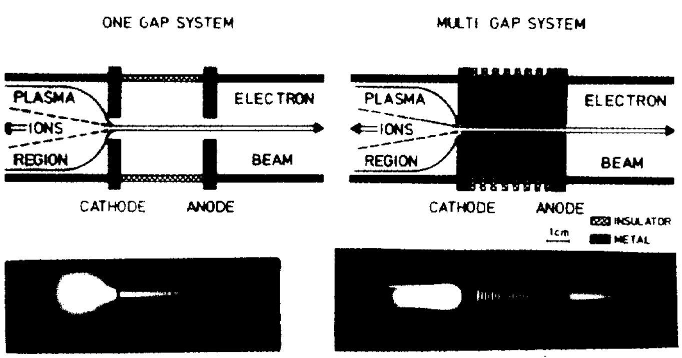


Fig. 1) Cross-sectional view (schematic, top) of a 2-electrode pseudo-spark chamber (left) and a multi-electrode pseudo-spark chamber (right), and corresponding open-shutter photographs.

If the system is operated on the left-hand side of the corresponding 'Paschen curve', the breakdown occurs (at a given pressure) on the longest possible path, which is located on the symmetry axis of the cathode hole. Long-path breakdown at other locations is avoided because of the insulator ring and a suitable isolating medium surrounding it (i. e. vacuum or high pressure gas). Such a system is called a (2-electrode) pseudo-spark chamber. A simple stack of electrode and insulator discs (fig. 1b, so-called multi-electrode system) shows improved performance as an electron beam source, possibly due to the higher gas pressure applicable in such a system.

The Pseudo - Spark

When a high voltage close to the breakdown voltage of the system described above is applied, a weak, low-current (-μA) predischarge develops on the axis of the system, this predischarge extends into the space behind the cathode, where it forms a region of positive space charge. Due to this positive space charge, a hollow cathode discharge (hcd) can be initiated at a high enough predischarge current (selfbreakdown) or by injection of additional charge carriers (triggered pseudo- spark). During this hcd, an energetic beam of runaway electrons is formed due to the high electric field and the focusing characteristics of the geometry. The acceleration of electrons is stopped when a highly conductive plasma channel on axis, created by the electron beam, short-circuits anode and cathode. The electron beam formation can be extended in time and beam current by additional capacitors connected to the pseudo-spark chamber, which sustain the electric field at a lower impedance level of the discharge. Therefore, the characteristics and the efficiency of converting electrical energy into electron beam energy depend on the properties of the discharge circuit. A time-integral photograph of the discharge shows clearly the typical hollow cathode discharge and the discharge channel on axis between anode and cathode (lower part of fig. 1).

Electron Beam Parameters and Beam Propagation

At a breakdown voltage of about 30 kV and more, the electron beam appears to be magnetically focused (pinched) by its own magnetic field, its radial current density distribution being close to a Bennett-profile /2/. Working gas is mostly argon, other gases, like He, Ne, Kr, Xe, N_2 and H_2, have also been used successfully. Typical dimensio of cathode hole diameter and electrode distance are 1 - 2 mm, the corresponding pressure for selfbreakdown at a voltage of several 10 kV depends on the number of electrodes and the type of gas, and ranges from several Pa to several 100 Pa. The electron pulse is composed of two parts: A low peak current, high-energy ($E \sim e{\cdot}U_{bd}$) part early in the discharge (fig. 2), which is

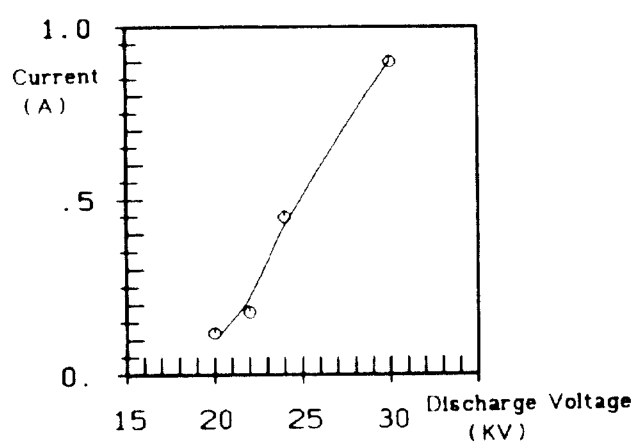


Fig. 2) Peak electron beam current of the first (pre-) pulse of the pseudo-spark, as a function of the discharge voltage, 15 mm behind the anode. The electron beam was produced in a 16-electrode system in argon, with an additional capacitor of 1 nF.

related to the hcd, and a high peak current pulse shortly after the first pulse, the amplitude of which is strongly dependent on the external capacitor (fig. 3). The mean kinetic energy of the electrons of the second pulse is of the order of $\sim 0.5{\cdot}e{\cdot}U_{bd}$. However, a large part of the **total** electron beam current shortly behind the anode belongs to low energy (several 100 eV to several keV) electrons, which can be deduced from the beam propagation behaviour (fig. 4a and 4b). The rapid decrease of charge transported by the electron beam is caused by the loss of low energy electrons due to scattering

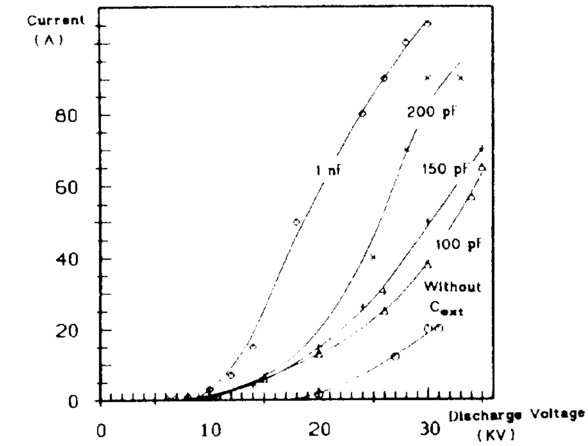


Fig. 3) Peak electron beam current of the main pulse as a function of the discharge voltage, for different capacitors C_{ext}, in argon.

(fig. 4a). The increase of transport efficiency with increasing discharge voltage (fig. 4b) indicates a relative increase of the high-energy part of the electron energy distribution function. In fig. 5, the influence of gas pressure and the type of gas on the beam transportation efficiency is shown; in hydrogen, the amount of total charge transported by the electron beam is of the order of 10%, and is almost independent on the pressure. In other gases, however, the gas pressure shows a strong influence at pressures higher than 50 - 100 Pa, where the beam transportation efficiency drops considerably, although the efficiency of electron beam **production**, particularly the peak current, increases with increasing atomic number of the gas.

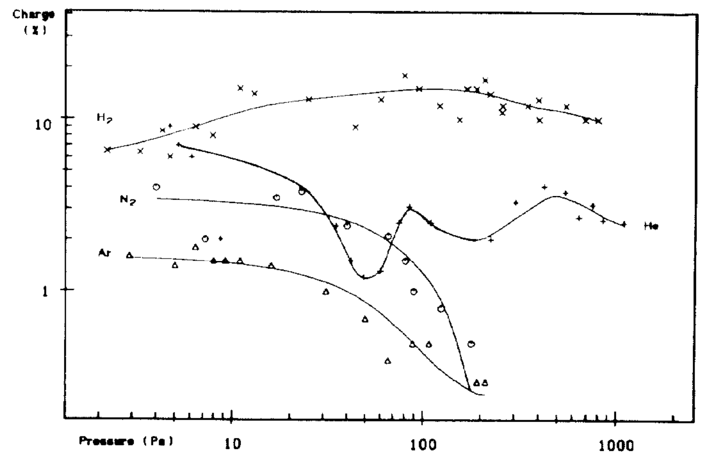


Fig. 5) Percentage of charge transported over a distance of 780 mm as a function of the pressure in the drift tube, for different gases. 16-electrode system operated at 30 kV and 1 nF C_{ext}.

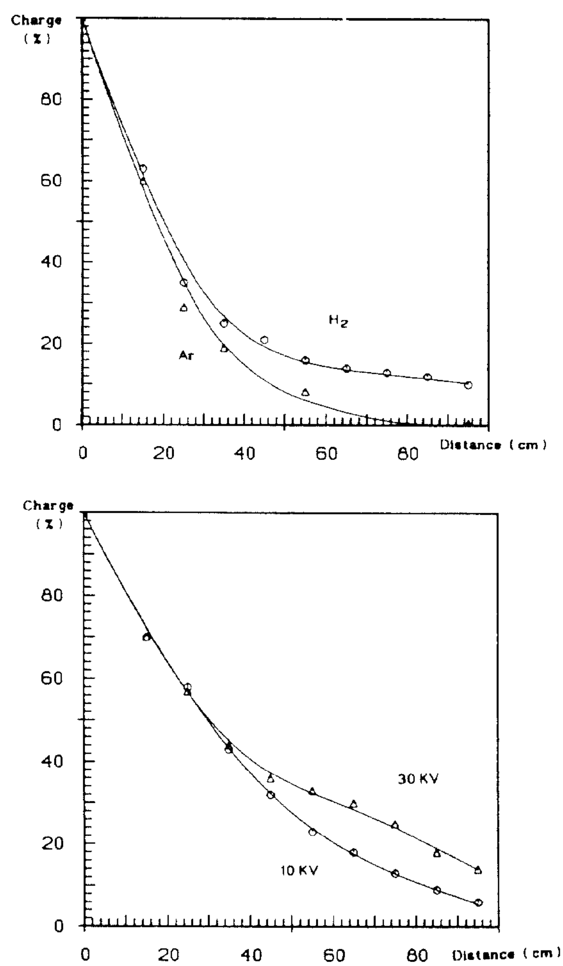


Fig. 4) Percentage of charge transported by the electron beam, as a function of the popagation length, 16-electrode system.

4a) comparison argon - hydrogen, 30 kV, without C_{ext}.

4b) comparison 10 kV - 30 kV discharge voltage, in hydrogen.

Beam - Target Interaction

The electron energy distribution function of the electron beam has been calculated for some specific cases /2/ from the results of bremsstrahlung spectrum measurements of the beam-target (thin (gas-) target) interaction. A typical result of time-resolved bremsstrahlung measurements is shown in fig. 6 for a breakdown voltage of 40 kV in argon; due to the poor energy resolution of the detector, no reasonable energy distribution function of the electron beam can be gained from these results. However, the temporal resolution is very good and gives a good impression of the temporal structure of the electron beam. In fig. 7, a time-integral electron energy distribution function of a discharge at 35 kV in argon is shown; a peak appears at the high-energy part of the spectrum, the main energy of the peak corresponding to the breakdown voltage. The maximum of the distribution function, however, appears at approximately 2/3 of the energy corresponding to the discharge voltage, indicating that the greater part of the electrons are accelerated during the later part of the discharge (i. e. during the breakdown phase of the electric field). (The lower energy limit of the spectrum is given by the low-energy cutoff of the aluminum window.) The total beam power, as calculated from the experimental results above, is of the order of 10^{6} - 10^{9} W. The radial density distribution of the beam can either be determined directly by means of a Faraday cup and a scanning aperture /2/, or by measuring the size of the interaction zone when the beam hits a solid target /3/. In fig. 8, the SEM photograph of an aluminum target is shown that was hit by a single electron beam pulse emitted by a pseudo-spark discharge; the 30-electrode pseudo-spark chamber was operated with argon of 10 Pa at a voltage of 50 kV. The distance anode-target is typically 15 mm. The superposition of a series of electron beam pulses leads to a crater formation ('hole drilling'), which is shown schematically in fig. 9. From these measurements, a beam diameter of - 0.4 mm FWHM can be concluded. This gives an estimated average beam current density of the order of 10^{6} A/cm^2. The table below summarizes the electron beam parameters which are reproducibly achieved in laboratory experiments.

pulse duration, FWHM	(nsec)	10
beam diameter, FWHM	(mm)	0.3 - 1
peak current	(kA)	0.1 - 1
max. electron energy	(keV)	- U_{bd}
mean electron energy	(keV)	$\hat{=}$ 0.5 - 0.7×U_{bd}
beam energy	(mJ)	10 - 100
current density	(A/cm^2)	- 10^6
power density	(W/cm^2)	-10^9
rate of current rise	(A/sec)	- 10^{11}

Table 1) Typical electron beam parameters of electron beams generated by pseudo-spark discharges

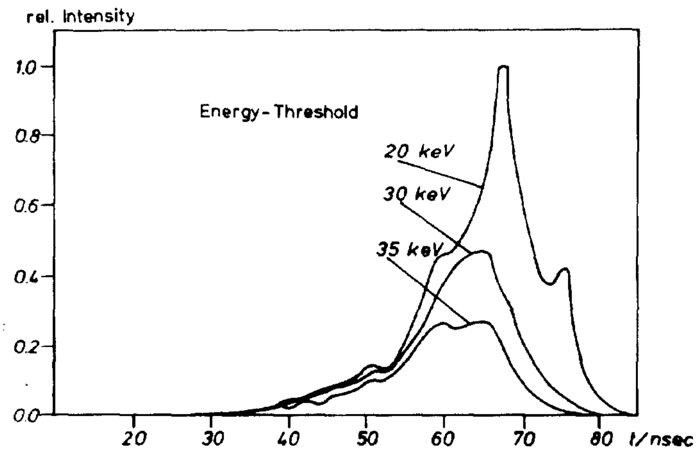


Fig. 6) X-ray signals from bremsstrahlung measurements of the electron beam-thin target (gas target) interaction, for different lower cutoff energies of the detector - analyzer system. 20-electrode system, argon, 40 kV, no C_{ext}.

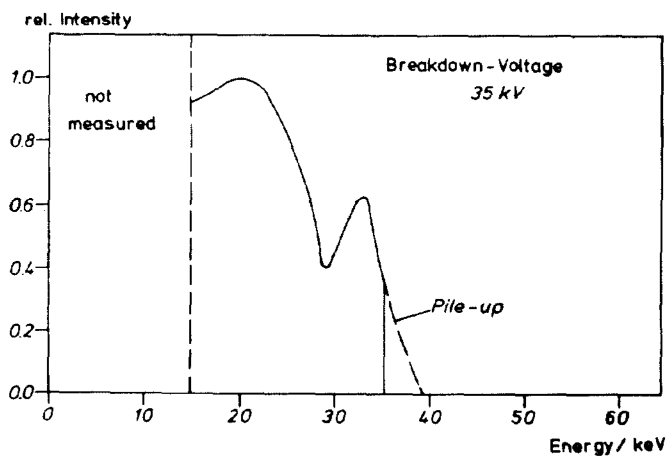


Fig. 7) Normalized time-integral electron energy distribution function of an electron beam as of fig. 6, for a breakdown voltage of 35 kV.

Conclusions

The pseudo-spark produces intense electron beams of short duration in a simple, inexpensive device with high efficiency. In a suitable geometry, it can be used as a reliable pulsed source of electrons for high-energy particle accelerators. The peak current seems to be extendable into the multi-kA regime, and 4.5 kA peak current electron beams have already been achieved in one experiment /4/. The resulting electron beams propagate in a self-focused manner in a low-pressure environment, which makes the application of (expensive) guiding magnetic fields unnecessary. From these considerations, the pseudo-spark seems to be a promising approach to a high brightness electron source for existing and future accelerators.

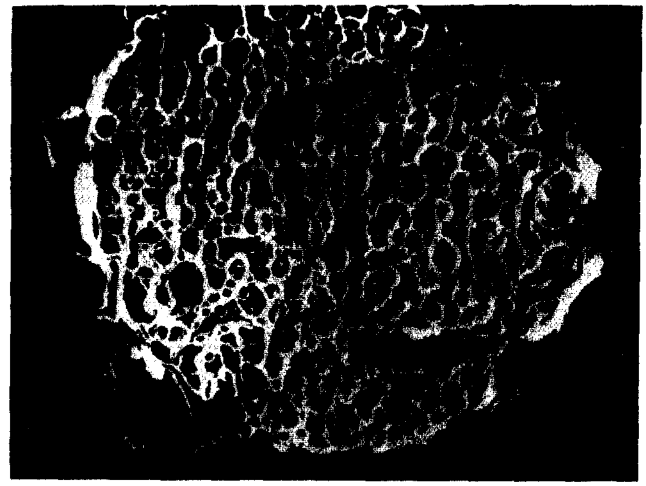
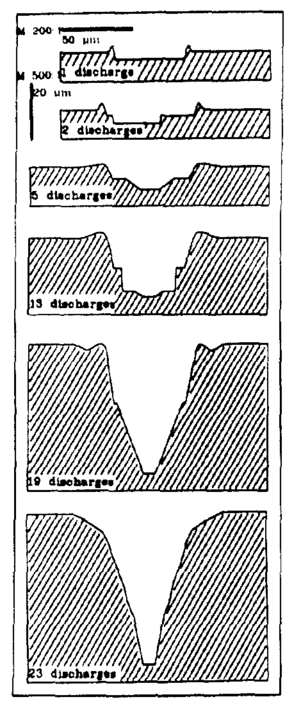


Fig. 8) SEM photograph of an aluminum target surface hit by a single electron pulse, the distance target-anode is 15 mm. 30-electrode system, -10 Pa argon, 50 kV, C_{ext} = 500 pF.

Fig. 9) Histogram of electron beam hole drilling with an electron beam as of fig. 8), shown is the profile of the surface after irradiation with different numbers of electron beam pulses (1, 2, 5, 13, 19 and 23 pulses, respectively).



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