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J. Bosser, R. Lapik*, R. Ley, I. Meshkov*, V. Poljakov*, I. Seleznev*, A. Smirnov*, E. Syresin*, G. Tranquille, and A. Zapunjako*,

Abstract

A new variable current electron gun has been developed in order to improve the performance of the LEAR electron cooler. The previous gun was of the resonant type offering little operational flexibility. The new gun is of the adiabatic type with the peculiarity that it has been designed to operate in a relatively low magnetic field. It allows for the online control of the electron beam intensity whilst ensuring low transverse and longitudinal temperatures. In this paper we report on the performance of the new gun in tests made at Lipetsk and at CERN, and we present the results of first cooling tests made at LEAR on proton beams at a momentum of 310.1 MeV/c.

* Visitors from CAPT-Lipetsk, Russia

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J. Bosser, R. Ley and G. Tranquille
PS Division, CERN, CH 1211 Geneva 23, Switzerland

R. Lapik, I. Meshkov, V. Polijakov, I. Seleznev,
A. Smirnov, E. Syresin and A. Zapunjako
Centre of Applied Physics and Technology, CAPT, 398055 Lipetsk, Russia

ABSTRACT
A new variable current electron gun has been developed in order to improve the performance of the LEAR electron cooler. The previous gun was of the resonant type offering little operational flexibility. The new gun is of the adiabatic type with the peculiarity that it has been designed to operate in a relatively low magnetic field. It allows for the online control of the electron beam intensity whilst ensuring low transverse and longitudinal temperatures. In this paper we report on the performance of the new gun in tests made at Lipetsk and at CERN, and we present the results of first cooling tests made at LEAR on proton beams at a momentum of 310.1 MeV/c.

1. INTRODUCTION

The variable current electron gun, developed between CAPT Lipetsk and CERN, is designed to generate a high quality electron beam with intensities of up to 3 Amps for electron energies up to 30 keV. The gun and its electrical connections are shown in Fig. 1. It consists of a 5cm diameter cathode surrounded by a Pierce electrode which are bot at full potential, the 'steering electrode' which is at a positive potential with respect to the cathode, and the 'exit electrode' which is at ground potential. The cathode potential essentially determines the mean energy of the electron beam and the steering voltage the electron beam intensity. This will be discussed in more detail in section 2. Table 1 lists the main parameters of the new gun.

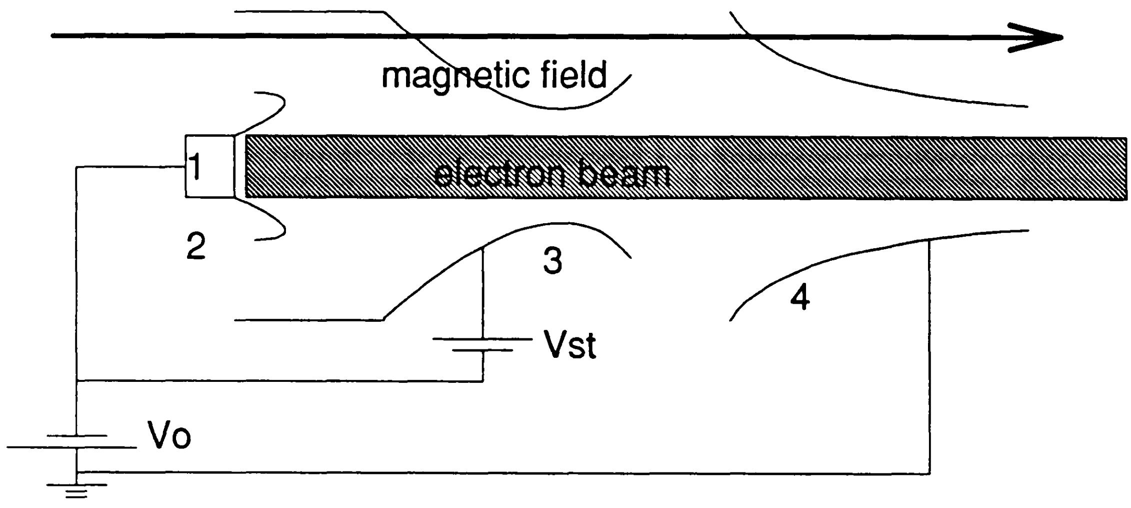

Figure 1. The electron gun. 1. cathode, 2. Pierce electrode, 3. steering electrode, 4. exit electrode

The gun was designed using the computer codes SAM [1] and EGUN [2], and by paying special attention to the shape of the steering and exit electrodes we were able to reduce the longitudinal field, in which the gun is immersed, to a relatively low value of 650 G. This is important for low energy operations at LEAR where we would be unable to compensate the coupling effect of the solenoid if the field were too strong. Computer simulations gave electron transverse energies of less than 0.4 eV, even with high intensity beams at low energy (3 Amps at 7 keV).

Table 1. Design parameters for the variable current electron gun.

Electron energy (keV)	2.3	7	20	30
Beam current (A)	0.01 to 0.53	0.07 to 2.93	0.35 to 2.83	0.65 to 2.6
Beam perveance (μP)[1]	0.125 to 5	0.125 to 5	0.125 to 1	0.125 to 0.5
Gun perveance (μP)[1]	0.58	0.58	0.58	0.58
Steering anode voltage (kV) [with respect to ground]	-1.45 to 8.1	-4.3 to 25.6	-12.5 to 11.5	-18.6 to 7.3

The gun offers a number of new facilities for the operation of the cooler :

1. the possibility to switch on and off the electron beam with the steering electrode without perturbing the circulating ion beam,
2. a very high current for electron beam energies lower than 20 keV,
3. the possibility to regulate the electron beam current during the electron cooling process.

As the electron intensity can be varied during beam cooling and with the possibility to neutralise the electron beam, a servo-system was implemented on the gun in order to maintain the mean energy of the electron beam constant. This system is described in detail in another paper presented at this workshop [3].

Because the cooler can now run with a fixed magnetic field, the compensation scheme was also modified when the gun was installed. The old tilted solenoids were replaced by a set of horizontal dipoles for the closed orbit correction and two straight solenoids powered in series with the cooler main solenoid. The whole ensemble is operated in the 'pulsed mode' as with the old system [4].

2. Parameter tests

Due to the fact that the electron intensity is determined by the steering electrode voltage, the important parameter describing the gun is the 'gun perveance' which is defined by

$$P_{gun} = I / V_{st}^{3/2},$$

where I is the beam current and V_{st} the steering electrode voltage. For a measurement of the perveance,the steering electrode voltage was fixed and V_0 varied in steps of 1 kV. For each step the beam current was measured and the gun perveance was calculated. Figure 2 shows the results for three values of V_{st}.

One sees that the gun perveance is significantly lower than the theoretical value of 0.58 μP for the regime when the steering electrode potential is positive with respect to the exit electrode i.e. with respect to ground (Fig. 3). This can be explained by the fact that when there is a positive potential difference, secondary electrons, created by collisions of the primary beam with the residual gas atoms, can be stored in this potential well and will limit the maximum beam current that the gun can deliver. This was confirmed by decreasing the cathode heating current whereby reducing the outgassing rate of the vacuum chamber around the gun which led to a slight increase of the beam current.

A value close to the design perveance could also be achieved by periodically pulsing the steering electrode voltage. If the steering voltage is forced to a negative value with respect to ground for a short period of time (<5 μs), the stored electrons are expelled from the well and the primary beam will increase in intensity. Secondary electrons will then slowly begin to fill the well and the primary beam current will decrease until the steering electrode is again pulsed. If the repetition rate for the pulser is about equal to the storage time for the secondary electrons, then the gun perveance can remain at more than 90% of the design value. The influence of this pulser on the cooling of ions has still to be tested but the effect is expected to be negligible.

The second parameter that we measured was the 'beam perveance' which is defined by

$$P_{beam} = I / V_0^{3/2},$$

[1] see section 2 'Parameter tests', for the definitions of beam and gun perveance

where V_0 is the cathode voltage. For this measurement V_0 was kept fixed and V_{st} increased until the design beam perveances shown in table 1 were obtained. Again we found that the nominal beam perveance could be reached but that the steering voltages necessary were much higher than the theoretical values (Fig. 4). The critical parameter was found to be the electron beam collector. It would seem that the collector perveance is much too low to recuperate effectively the dense electron beams that can be generated by the new gun.

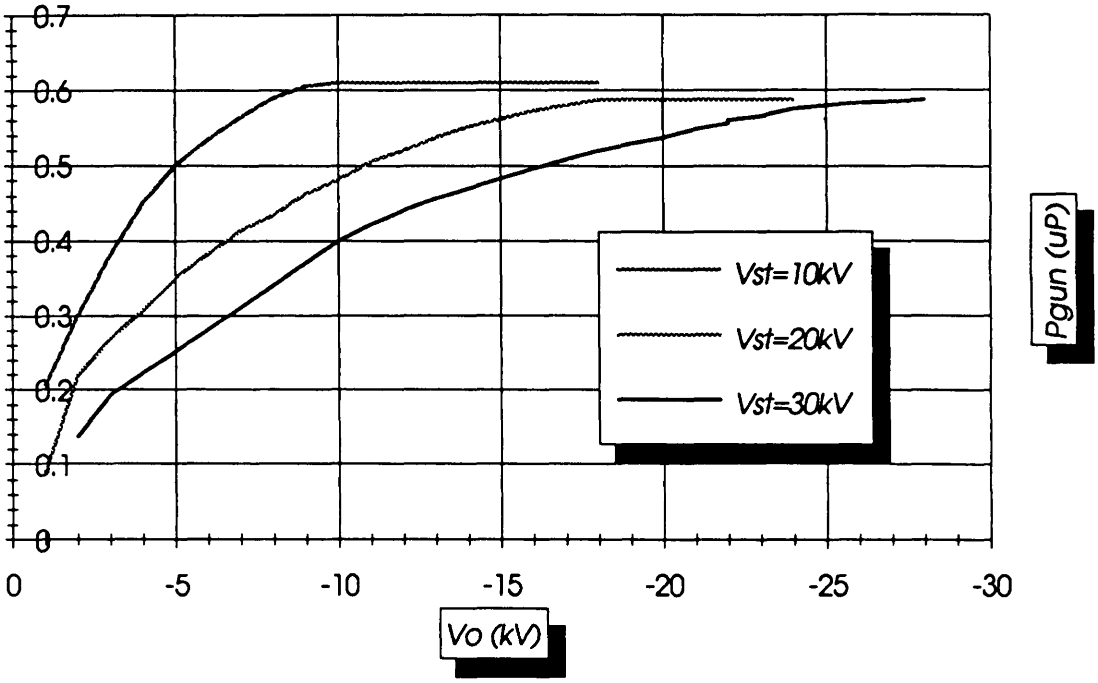

Fig 2. The variation of the gun perveance, P_{gun}, as a function of the cathode voltage V_0 for fixed values of the steering voltage V_{st}.

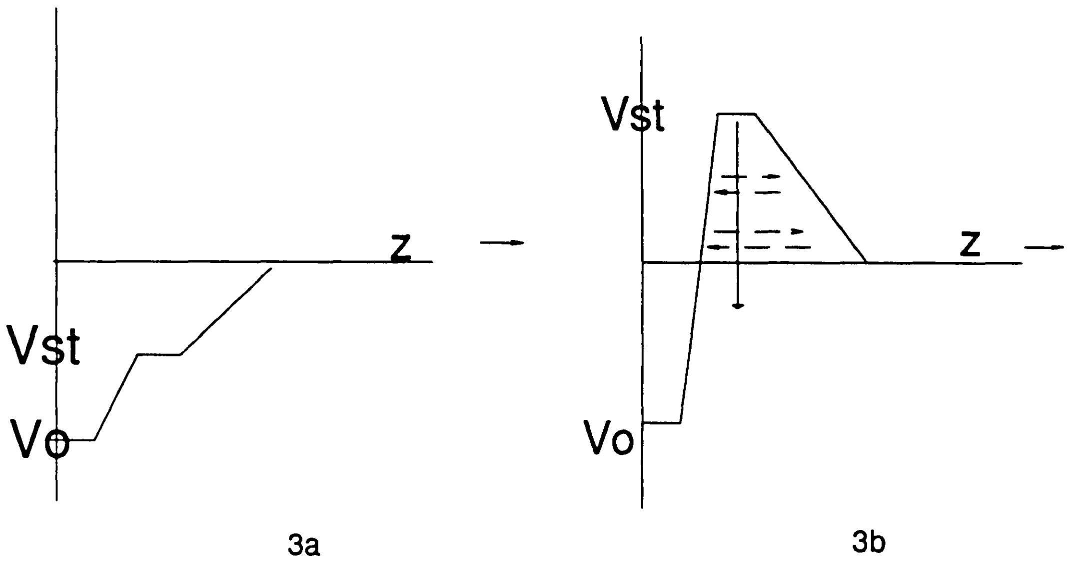

Fig. 3 The potential distribution on the beam axis. 3.a. shows the case when the electrons are smoothly accelerated to the desired energy and 3.b. shows the case when a potential well for secondary electrons is created when the steering electrode potential is positive with respect to the exit electrode. If the steering potential is made negative for a short period of time then the well no longer exists and the secondary electrons can escape.

More recently, after a fine adjustment of the collector and repeller voltages, a beam perveance of 2.8 μP was obtained at an electron energy of 10 keV. With a steering voltage of 30 kV, this corresponds to a gun perveance of 0.58 μP which is in perfect agreement with the simulations.

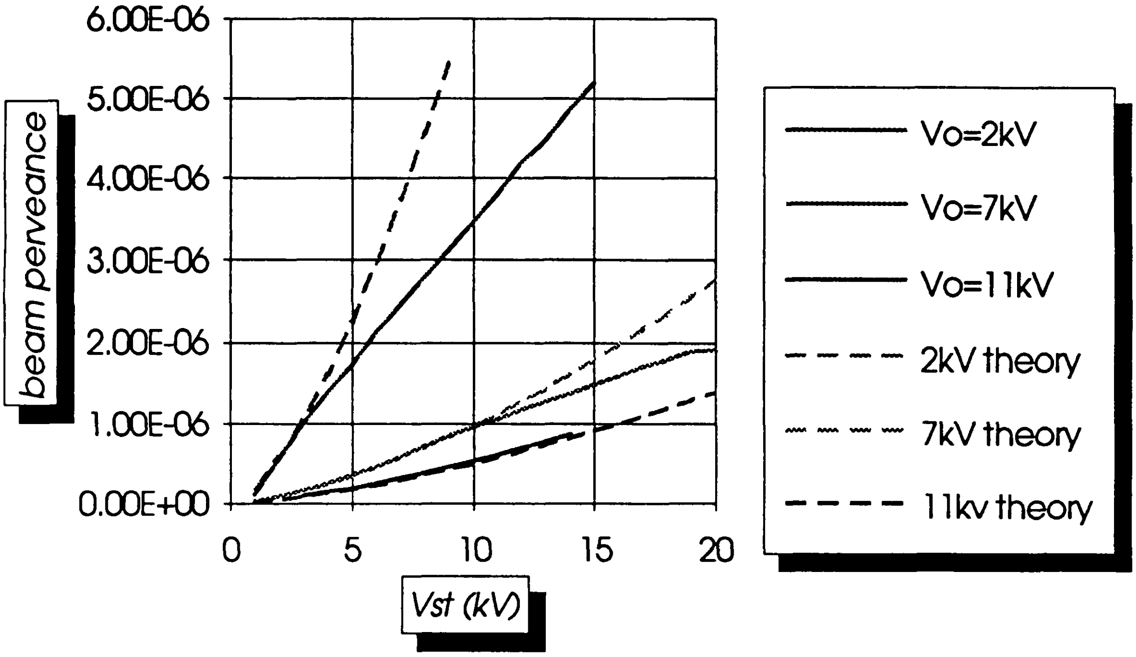

Fig 4. The dependence of the beam perveance, P_{beam}, on the steering voltage V_{st} for fixed values of the cathode voltage V_0

3. Cooling tests with 50 MeV protons

Once the parameter tests had been concluded, electron cooling tests were made at the proton injection energy of 50 MeV. A number of measurements were made in order to determine the real possibilities of electron cooling with the new gun. They comprised emittance and cooling time measurements in the transverse and longitudinal planes as a function of electron beam intensity, as well as tests on the servo-system and experiments on beam neutralisation.

3.1 Emittance measurements

During electron cooling of protons the neutral hydrogen beam, formed by the recombination with the cooling electrons, can be observed with multiwire proportional chambers or solid state detectors. This allows the shrinkage of the proton beam to be observed during cooling and one can also directly measure the equilibrium beam size. Figure 5 shows the vertical and horizontal H^0 profiles measured by a CCD camera placed at the end of the cooling section in LEAR. The video signal is displayed on a digital oscilloscope and from there it can be acquired and analysed by a program running on the LEAR μVAX cluster. The measured equilibrium emittances (2σ) were found to be $\varepsilon_v = 6.3\ \pi$ mm mrad and $\varepsilon_h = 4.3\ \pi$ mm mrad.

3.2 Cooling time measurements

The transverse and longitudinal cooling times were measured by observing the evolution of the spectral density of the beam Schottky noise around frequencies corresponding to a harmonic of the revolution frequency or a transverse sideband. This method has been used in previous cooling experiments [5] and was found to be very accurate as long as there are no beam instabilities. The measurements were made at injection, where the emittances are the largest, and the cooling time to equilibrium was estimated from the Schottky scans. Taking advantage of the fact that the electron beam intensity could be varied online, we also measured the dependency of the cooling time on this parameter. Figure 6 shows the results obtained for three settings of the electron beam current and for two different proton beam intensities. The initial values of the transverse emittances were estimated to be about 45 π mm mrad in each plane, and the momentum spread was measured to be 4×10^{-3}.

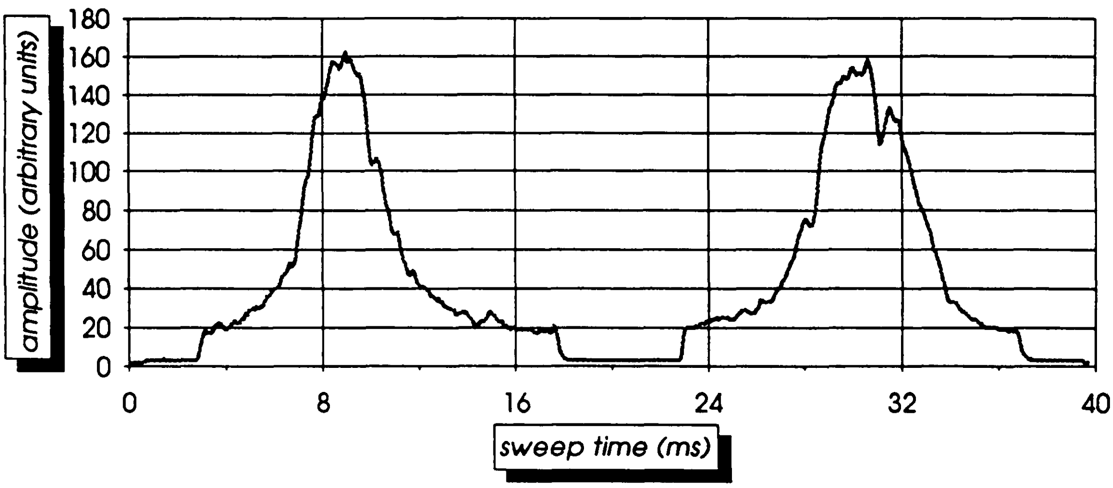

Fig 5. Vertical (left) and horizontal (right) H^0 profiles. One video signal scan takes 40 ms which is equivalent to a width of 14.3 cm. By converting the FWHM from ms to cm one obtains the equilibrium emittances.

From the results it would appear that for the transverse cooling time measurements the 1/I dependency does not satisfactorily fit the mesaured values. In the longitudinal plane however the theoretical curve agrees very well with the measurements. Moreover there seems to be a relationship between the cooling time and the number of stored protons. The difference could be due to the fact that we measured the total cooling times and not the e-fold cooling time, which is normally used. The method used for the measurement also has to be refined as the longitudinal cooling greatly influences the transverse Schottky signals. More measurements will need to be performed in order to confirm the observations already made.

3.3 Evaluation of the space charge contribution

Due to the space charge of an intense electron beam, in order for electron cooling to proceed at the correct energy the cathode must be placed at a slightly higher value than the mean kinetic energy of the electrons. The exact contribution of the beam space charge can be evaluated by varying the electron beam intensity and measuring the change in momentum of a circulating proton beam on a spectrum analyser. This momentum change is directly proportional to the mean kinetic energy of the electrons.

Figure 7 shows the variation of the space charge contribution to the electron beam energy as a function of beam intensity. The measured curve differs somewhat from the theoretical relation of $U_{sp} = 91.83I/\beta$. At high currents the contribution begins to saturate and for lower currents the behaviour follows the linear relation $U_{sp\ meas} = 78.85I/\beta$.

4. Conclusions

The variable intensity electron gun has proved to be an invaluable tool in the operation of the LEAR electron cooling device. The possibility to regulate the beam current not only opens new possibilities for cooling at ultra low energies, but has also enabled us to make a series of interesting measurements on the cooling times of protons and to investigate the influence of the electron beam space charge. The stability of stored beams should also be less of a problem as we are able to reduce the electron beam current, hence the cooling strength.

It has not yet reached the full design specifications (especially for low energy electron beams) but recent results make it clear that through careful adjustment of the cooler parameters we will soon reach the design specifications.

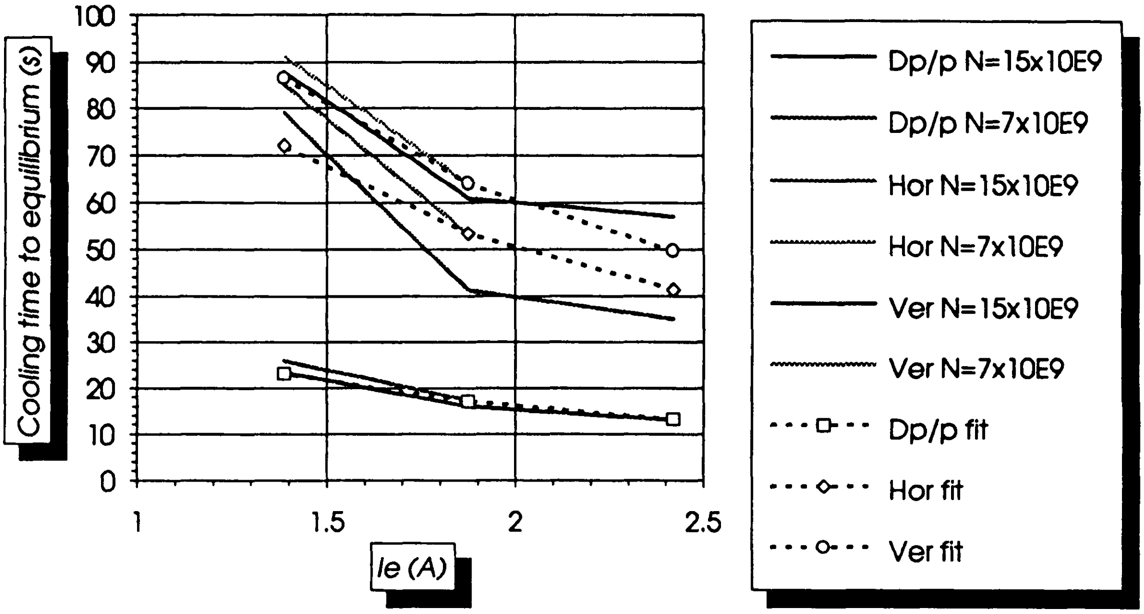

Fig 6. Cooling times to equilibrium for a proton beam at 50 MeV as a function of electron beam intensity.

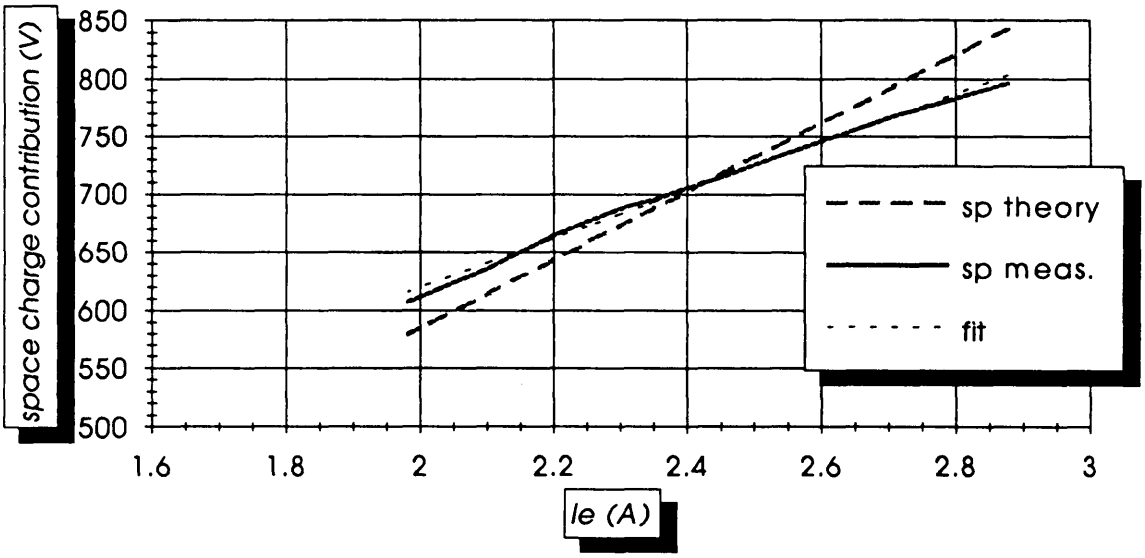

Fig 7. The space charge contribution as a function of electron beam intensity at 26.9 keV.

4. References

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