Rutherford Laboratory

Technical Leaflet

A18

MAXIMUM CURRENT IN AN ELECTRON BEAM

An experimental answer has been sought to the question "what is the maximum current of electrons which can flow from one place to another in a vacuum?"

The reason why the current in such a beam is limited at all is that the electrons, being electrically charged, tend to repel each other. Thus an initially parallel beam of electrons spreads as it moves forward: the higher the current the greater the spread. For extremely high currents, many of the electrons are turned round completely and return to the electron source or gun.

In the experiment demonstrated here the situation has been simplified by providing a strong longitudinal magnetic field to prevent the beam from expanding sideways. Thus the electrons are forced to move along the magnetic field lines and this makes the problem easier to understand theoretically, as does the provision of a cylindrical drift tube in which the beam flows. However, the space charge forces still act on the electrons, only now the effect of increasing the injected current is to slow down the electrons in the drift space until, when their velocity has fallen to about half its initial value, the beam quite suddenly becomes unstable: some of the electrons are brought to rest in the drift space and are forced to return to the cathode, the beam becoming partially hollow. This effect occurs at a surprisingly low value of current: for example in the apparatus shown here (beam filling the drift tube), a beam of 100 eV energy becomes unstable at about 30 mA. For other electron energies V (electron volts), the maximum current is $32 \times 10^{-6} V^{3/2}$ amps.

Neutralization of space charge

This space charge limitation can be overcome if positively charged particles are added to the beam so that the densities of positive and negative charge are equal. Given sufficient time, this 'neutralization' of an electron beam occurs automatically, even in a high vacuum, provided that the electrons in the beam have an energy high enough to create positive ions by collision with residual molecules of gas in the vacuum system, and also provided that the beam is in a region free of electric fields which could extract ions from it. (The secondary electrons created in the ionising collision quickly leave the beam.)

It might be expected that under these conditions almost unlimited currents could flow. However, the experiments show that a new limit is reached, when the beam suddenly becomes catastrophically unstable at only about six times the limiting value in the absence of ions. The limit is caused by an electrostatic wave interaction in which, due to the Doppler effect, the plasma frequency of the electrons in the moving beam is reduced in the stationary frame of reference so much that the electrons appear to be oscillating at the same frequency as that of an allowed mode of the ions. As the electron current is increased, so the wavelength of the oscillation decreases: when this wavelength becomes reduced roughly to the physical length of the drift space, the wave amplitude grows extremely rapidly till the whole beam is disrupted and a substantial fraction of the electrons are returned to the gun.

More details of the apparatus being demonstrated can be seen from the figure accompanying it.