A03 Determination of the specific charge of electrons (e/m)

H. Bender, V. Braun, B.Appelton Fachhochschule Oldenburg / Ostfriesland / Wilhelmshaven, University of Applied Sciences, Emden, Germany
Engineering Physics Course

Version: January 23, 2002

2.1 Introduction

2.1.1 Aim of the Experiment

The electron's specific charge is to be determined by measuring the trajectory of an electron beam in a homogenous magnetic field.

2.1.2 Tasks

- Measure the magnetic flux density B inside a pair of Helmholtz coils as a function of the excitation current I_{exc}.
- Measure the accelerating voltage U for a constant electron path radius in relation to the magnetic flux density B and determine the specific electron charge $\frac{e}{m_e}$

2.1.3 Note

The order in which the specified tasks are to be carried out depends upon the initial state of the set-up. If the electron beam system is already inside the Helmholtz coils, the electron beam measurements should be taken first, then after carefully removing the electron beam system, the magnetic field measurements.

2.2 Theory

2.2.1 Electrons in magnetic field

A particle with mass m, charge q and velocity $\vec{v}$ is injected into a homogenous magnetic field (flux density $\vec{B}$) at right angles to the field vector. The Lorentz force acting on the particle

$$\vec{F_L} = q \cdot (\vec{v} \times \vec{B}) \tag{2.1}$$

is always at right angles to $\vec{B}$ and to the particle's momentary velocity $\vec{v}$. Therefore the particle's kinetic energy remains constant and it follows a circular orbit of radius r in a plane at right angles to $\vec{B}$. As a result of the orthogonality, the following also applies

$$\left|\vec{F_L}\right| = \left|q \cdot \vec{v} \cdot \vec{B}\right| \tag{2.2}$$

In the circular orbit the Lorentz force acts as a centripetal force. For electrons with mass m_e follows

$$e \cdot v \cdot B = \frac{m_e v^2}{r} \tag{2.3}$$

which can be transposed to give the specific charge

$$\frac{e}{m_e} = \frac{v}{B \cdot r} \tag{2.4}$$

The electron injection velocity v is directly related to the accelerating potential U. The initial velocity is ignored (thermal electrons). With the energy equivalence

$$eU = \frac{1}{2} m_e v^2 \tag{2.5}$$

set in equation 2.4 the specific charge becomes

$$\frac{e}{m_e} = \frac{2U}{B^2 r^2} \tag{2.6}$$

2.2.2 The narrow beam tube

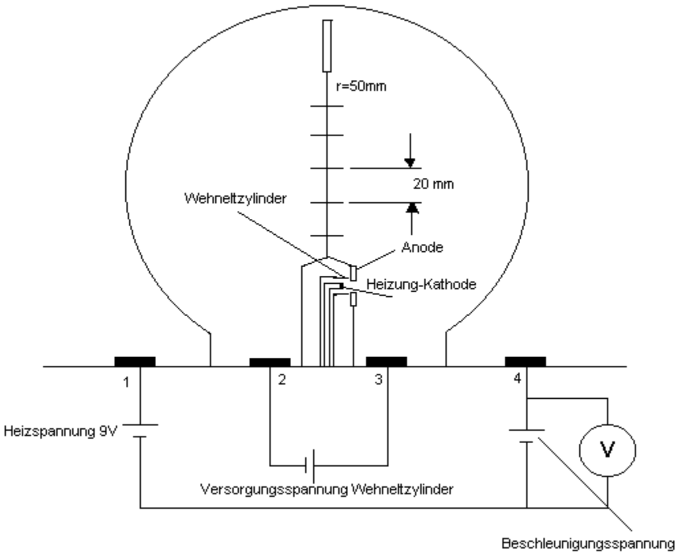

Figure 2.1: narrow beam tube

A narrow beam tube consists of a glass sphere containing an electron beam device, measurement markings and the inert gas neon at a residual pressure of approx. 1.3 Pa. If the narrow beam tube is placed in a homogenous magnetic field, the electron beam which it produces can, under certain conditions, be deflected into a circle. The main components of the electron beam system are the thermionic cathode, ring anode and Wehnelt cylinder, the functions of which will now be described. The electrons required for the beam are emitted from the thermionic cathode. The cathode is heated by an electric current produced by the applied heater voltage and the electrons are ejected from the cathode surface by thermal emission. The application of a positive voltage to the anode causes the electrons to be accelerated towards it. The Wehnelt cylinder and the ring anode form an electrostatic lens which focuses the electron beam, which then leaves the system through the hole in the anode. The electrons' kinetic energy is given by equation (2.5). Because of the tube's gas filling, the electrons cannot travel freely. Many of them collide with the sluggish, neutral gas atoms and this produces positive ions along the electrons' trajectory. Because of the relatively low mobility of the gas atoms, a low-space-charge channel is formed, which in turn increases the electrons' range in the residual gas. This process is called gas constriction. The electrons still collide with some gas atoms, which causes them to glow. If the

narrow beam tube is placed in a homogenous magnetic field with the flux density B, the electron beam is deflected by the resulting Lorentz force. When the set-up is adjusted optimally, the force deflects the beam into a circular orbit with radius r.
The descriptions and literature values for the parameters of equation 2.5 are now given in advance. This however should not deter one from carrying out the experiment.

m_e = electron mass = $9.10953 \cdot 10^{-31}$ kg
e = electron charge = $1.60219 \cdot 10^{-19}$ As
U = anode voltage
v = electron velocity

2.2.3 Theoretical calculation of the magnetic flux density

B can be calculated theoretically on the basis of the Helmholtz coils' geometry, with the following equation. (This is strictly only valid for the center of the set-up):

$$B = \mu_0 \cdot N \cdot I \cdot \frac{R^2}{(R^2 + a^2)^{\frac{3}{2}}} \tag{2.7}$$

with:

N = number of turns per coil = 124
I = coil current in A
R = mean coil radius = 142.5 mm
$2a$ = mean coil spacing = 150.0 mm
μ_0 = magnetic constant = $1.2566 \cdot 10^{-6}$ Vs/Am

If these values are set in equation 2.7 one obtains the following value for the coil factor:

$$\frac{B}{I} = 7.48 \cdot 10^{-4} T/A \tag{2.8}$$

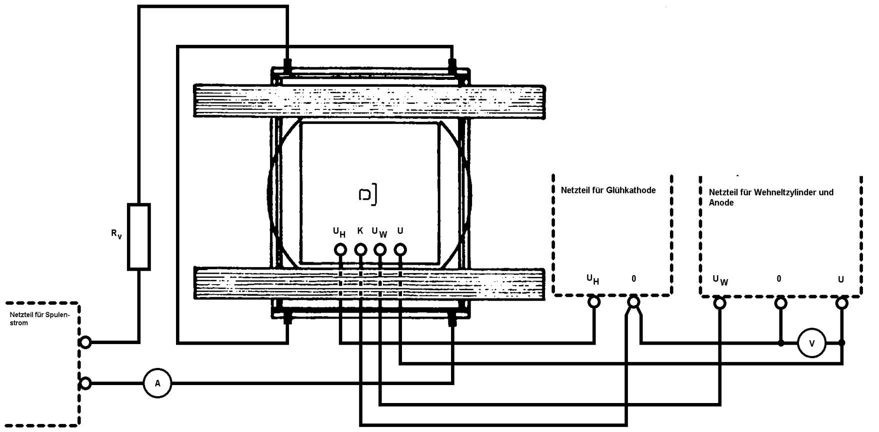

Figure 2.2: Fadenstrahlrohr in der Helmholzspule

2.3 Experiment

2.3.1 Measurement with the narrow beam tube

- Switch on the magnetic field measurement device. Take note of the zero drift plot on the right-hand side of the case.

- Pass the narrow beam tube, with it's foot facing forwards, through the front coil and place it between the coils. Connect the tube according to fig. 2.1 and get the supervisor to check the connections.
- Set the voltage control on each of the power supply units to it's minimum (full anticlockwise) before switching it on. The power supply for the thermionic cathode takes several seconds to reach a steady voltage.
- Place the light-shield over the set-up and, while observing the voltmeter, slowly increase the anode voltage U to it's maximum value (approx. 370V). A narrow neon-blue coloured beam can be seen to form. By increasing the coil current, the beam can be deflected into a circle.
- For each of ten different anode voltages, the coil current is to be adjusted so that the beam touches the markings for the radiuses of 30, 40 and 50 mm in the tube as exactly as possible.

Note: If the electrons are deflected in the wrong direction (downwards) then the current in the Helmholtz coils must be reversed. If the beam follows a helical, rather than a circular trajectory, the initial velocity vector $\vec{v}$ of the electrons is not at right angles to $\vec{B}$. This can be corrected by carefully turning the narrow beam tube around it's vertical axis.

2.3.2 Measuring the magnetic field between the coils

After removing the narrow beam tube, the Hall element sensor and magnetic field measurement device should be used to measure the magnetic field distribution (H) and flux density (B) in the coil set-up.

- The homogeneity of the magnetic field is to be investigated for three different coil currents.
- In order to determine the coil constant B/I, the magnetic flux density B is to be measured at different coil currents.

2.4 Experimental apparatus and specifications

The following apparatus is provided to carry out the tasks listed above:

1. 1 narrow beam tube,
   specifications:
   tube diameter 165 mm, height incl. baseplate 260 mm, anode voltage + 200 to 400 V, heater voltage approx. 10 V, Wehnelt voltage approx. 7 V, anode current <0.3 mA, heater current 150 to 200 mA, beam orbit diameter max. 100 mm, beam radius mark spacing 20 mm.
2. 1 pair Helmholtz coils,
   specifications:
   mean coil spacing 150 mm, outside diameter 307 mm, inside diameter 283 mm, mean radius 142.5 mm, wire diameter 1.5 mm, ohmic resistance 1.2 Ω, turns per coil 124, max. current 3 A.
3. 3 power supplies
4. 2 multimeters
5. 1 magnetic field measurement device with Hall probe

2.4.1 Note

The magnetic field measurement device should be switched on around a half-an-hour before the measurements are to be made, in order to be sure that it will have adequate zero stability. For the first measurement, the Hall probe should be positioned so that the H-field measurement device shows a maximum reading. After this the Hall probe should only be moved parallel to the coils.

2.5 Analysis

- Calculate e/m_e (mean value, error).
- Plot B(x) and B(y).
- Plot B(I). Use the plot to calculate the coil constant and the slope B/I.

2.6 Questions / key topics

Hall effect - do relativistic effects occur? Movement of electrons in electromagnetic fields, gas focussing, vector product. Number of electrons emitted, consideration of units - how does one come from eq. 5 to the unit for the specific electron charge As/kg.