15 Equipment for Beam Diagnostics

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15.1 Introduction

The ion beam from an electrostatic accelerator is described by the following parameters:

– species of ion, its charge state and energy
– beam current
– beam profile (diameter, position and intensity distribution)
– emittance and brightness
– energy spread
– stability in position and current.

During accelerator operation, not all beam characteristics can be measured with a reasonable number of instruments. Fortunately, the optimization process of the accelerator and the beam transport system requires only the measurement and control of some of the parameters.

The main parameters of an ion beam are the species, charge state and energy. Usually, it is assumed that these values are clearly determined by the operation of the ion source and the stabilized field of the deflecting magnets in connection with the acceleration voltage. Consequently, these parameters are not continuously observed during accelerator operation. Unfortunately, a mistake in this area can lead to wrong results and economic losses. Some reasons for such troubles are unexpected leaks or contaminated materials in the ion source, which result in additional oxide or hydride ions in the ion spectrum from the source. Therefore, the check of the ion spectrum from the source or in the accelerated beam should not be neglected, especially after maintenance of the ion source or a change of the ion source material.

The emittance and the brightness of an ion beam are influenced mainly by the properties of the ion source, the acceleration voltage and, in the case of tandem accelerators, the stripper density. Their values cannot be directly influenced during accelerator operation and therefore do not need to be measured continuously. Emittance measurement devices are preferably installed in ion source test stands [1]. The sources of energy instabilities and their monitoring on a display using a capacitive pickup electrode are described in Chap. 9.

In the following explanations, the experience of more than 30 years of operation and development of the electrostatic accelerators at the Forschungszentrum Rossendorf, Dresden, Germany, is summarized and focused on the necessary and appropriate equipment for beam diagnostics for electrostatic accelerators, especially for measurement and monitoring of the current, position, stability and profile of the ion beam.

15.2 Measurement of the Beam Current

The measurement of the particle current is the most important diagnostic tool. It is necessary for:

- optimizing the accelerator operation (ion source output, transmission, and beam transport system)
- calculation of the implanted fluence or as a monitoring parameter for ion beam analysis.

The beam current can be measured by destructive and nondestructive techniques. The destructive techniques can be separated into total beam-stopping devices (Faraday cups) and partially stopping devices (scanning wires and rotating-sector discs). A nondestructive technique is the measurement of the residual-gas ionization. In the case of bunched beams, the current can be measured nondestructively by capacitive pickup devices or by induction coils. Bunched beams are generated with electrostatic accelerators mainly for special applications (time-of-flight measurements) and are not considered in the following.

15.2.1 Faraday Cups

Faraday cups (FCs) are the most commonly used devices for beam current determination. The particle beam is collected in an insulated cup and measured with a conventional DC measuring technique. The design of a Faraday cup is concerned with the suppression of disturbing currents to or away from the collecting cup. Such parasitic currents are generated by:

- secondary electrons or ions from the entrance aperture or the bottom of the cup
- leakage currents from the suppression electrodes
- leakage currents from the cooling water
- charged particles from the residual gas
- thermal emission of electrons from heated surfaces.

Electrostatic and magnetic fields are applied for the suppression of secondary particles. A conventional Faraday cup with electrostatic suppression is shown schematically in Fig. 15.1. To prevent any secondary-electron emission from the suppression electrode (2), its inner diameter must be bigger

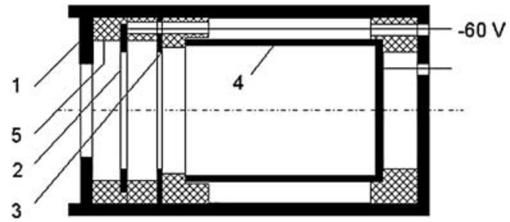

Fig. 15.1. Faraday cup with electrostatic electron suppression: 1, entrance aperture; 2, suppression electrode; 3, grounded separation electrode; 4, measuring cup

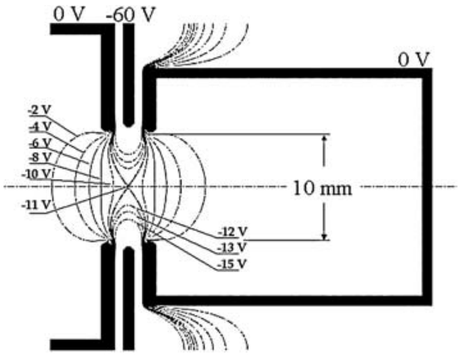

Fig. 15.2. Calculated potential distribution in an FC with electrostatic suppression

than the diameter of the entrance aperture (1). Secondary electrons cannot leave the FC (4) if the potential barrier on the optical axis exceeds their corresponding maximum kinetic energy. This potential on the axis is not identical to the potential of the suppression electrode and depends on its inner diameter and length. The calculated potential barrier on the optical axis of the FC in Fig. 15.2 is about $-11\,\mathrm{V}$, while the potential at the suppression electrode is $-60\,\mathrm{V}$. Electrons with energies of about $12\,\mathrm{eV}$ can pass through the entrance opening of the FC. Therefore, the beam current measured with an FC tends to a saturation current (Fig. 15.3) at suppression voltages which are higher than the maximum energy of about $10\,\mathrm{eV}$ of the secondary electrons. Additionally, the negative electrode collects secondary positive ions from residual-gas ionization and from the bottom of the cup, resulting in deviations of the measured current (the saturation current in Fig. 15.3) from the real beam current. In comparison with the generation of secondary electrons, this effect has a lower influence, but it must be considered for high-precision measurements.

The secondary electrons and ions can also be suppressed by magnetic fields. Under the influence of a transverse magnetic field generated by permanent magnets, the secondary particles move on bent trajectories and cannot leave the FC. A remarkable deviation of the measured current from

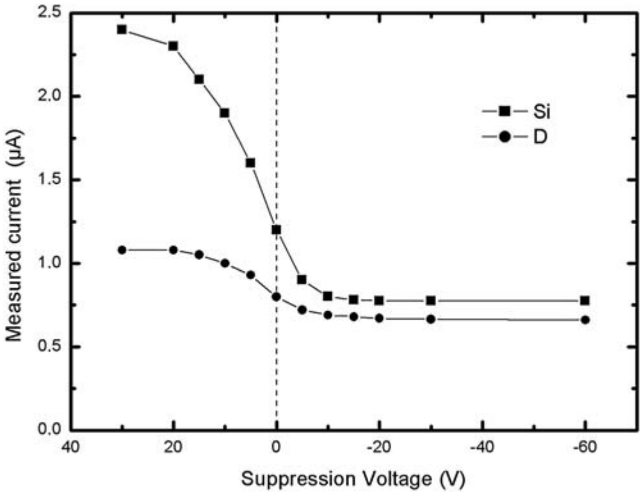

Fig. 15.3. Dependence of the measured beam current on the suppression potential for 0.7 MeV $^{2}H^{+}$ and 3 MeV Si^{2+} ions. The beam currents at positive suppression voltages indicate the different secondary-emission efficiencies

the expected value may occur if the cup is located behind an aperture (a slit device or the entrance aperture of the cup) or if the residual-gas ionization is sizable. Owing to the internal resistance of the DC measuring device, the ion beam generates a positive potential at the Faraday cup. This potential collects secondary electrons from the aperture or from the residual gas, respectively. Therefore, the measured beam current is lower than the real ion current. An additional electrostatic suppression electrode at the entrance of the FC can reduce this effect. On the other hand, the positive potential generated by the ion beam collects secondary electrons emitted from a cup or an isolated piece of quartz and improves the precision of current measurement with these devices. Using different resistors adapted to the expected range of the beam current, the current signal from an isolated screen or an FC without secondary-electron suppression can be applied in the same manner as that from an FC with additional electron suppression for optimization of the operation of the accelerator.

The arguments for and experiences with different electron suppression techniques can be summarized as follows:

– Faraday cups with electrostatic suppression of secondary electrons are versatile devices for beam current measurement.
– Faraday cups with magnetic suppression can be applied advantageously if the generation of electrons by residual-gas ionization can be neglected and no aperture is located in front of the cup.
– The influence of apertures in front of an FC with magnetic suppression can be reduced by additional electrostatic suppression.

– The potential generated by isolated beam-stopping devices can be used to improve the beam current signal from these devices.

Leakage currents can influence the measured beam current. To reduce this effect, any direct insulator connection between the suppression electrode and the measuring cup must be prevented. This can be realized by an additional grounded electrode (3 in Fig. 15.1), which collects leakage currents from the suppression electrode. This detail is neglected at some commercial FCs and the modification of these cups is nearly equivalent to a new construction.

For high beam power, the cup must be cooled. In order to reduce disturbing influences and leakage currents, distilled water or compressed air is commonly applied. For precise low-current measurements, a cooling-water line is not necessary and can be interrupted. For this purpose, the use of quick-disconnect cooling lines is advisable. If the FC is constructed using materials of high melting point (e.g. tantalum), the heat can also be removed by thermal radiation. Commercial devices based on radiation cooling are available for up to 50 W beam power [2]. A disadvantage of the radiation-cooling method is the possible gas desorption from the beam line wall, causing beam degradation.

Besides the suppression of secondary electrons, the problem of removing the FC from the beam axis has to be considered in the construction of an FC. Some commonly applied methods are used at the Rossendorf electrostatic accelerator and can be compared after several years of operation:

– In the 2 MV Van de Graaff accelerator, the FCs (or insulated quartz disks) are lifted by the magnetic field of solenoids.
– The beam diagnostic elements for the 5 MV tandem accelerator were originally equipped with electric motors.
– All retractable FCs in the 3 MV Tandetron are equipped with pneumatic cylinders.

Owing to the switching time of several seconds for motor-driven diagnostic elements, this method is not applied anymore. The switching time and reliability of the devices with magnetic solenoids and those operated with compressed air are comparable. Since pneumatic cylinders are commercially available, this method has been used in reconstruction and enlargement of the beam lines.

15.2.2 Nondestructive Beam Current Measurement by Residual-Gas Ionization

Owing to interaction of the accelerated ions with the residual gas, electron–ion pairs are generated along the beam trajectory. These electrons and ions can be separated by a transverse electric field and detected with particle detectors, Faraday cups or channel-plate amplifiers (Fig. 15.4). The ionization efficiency depends linearly on the residual-gas pressure and is also influenced

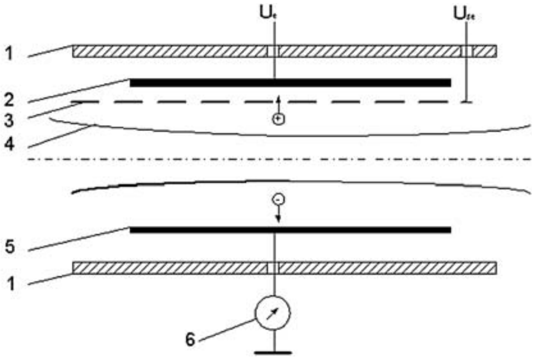

Fig. 15.4. Principle of beam current measurement using residual-gas ionization: 1, beam line wall; 2, extraction electrode; 3, secondary suppression electrode (optional); 4, ion beam; 5, collecting electrode; 6, current measurement

by the atomic number and energy of the accelerated primary ions. Owing to the calibration necessary for beam current measurements, this nondestructive method is not applied over a wide range, but it appears as a basic principle in particle detectors (gas-filled ionization chambers). A special modification for beam profiling is described in Sect. 15.4.2.

15.2.3 Partially Destructive Beam Current Measurement

The interruption of the ion beam during measurement with an FC can be reduced using an off-axis FC and short-time electrostatic deflection of the beam into the cup. This method is preferably applied when there is a constant beam current. If the beam is unstable, the average value of the beam current must be determined in fast, short sequences. This can be realized by measuring the beam particles backscattered from a rapidly rotating sector disk plated with gold (Fig. 15.5). Thereby, the ion beam is reduced by the ratio of the area of the sectors to the area of the full circle. The count rate of the backscattered particles can be converted into the real beam current by calibration using an FC. At experiments with variation of the ion energy E, the dependence of the counting rate on E^{-2} must be taken into account.

15.3 Monitoring of the Beam Diameter and Position

A simple device for observation of the beam diameter, position and stability is a screen which emits light under irradiation with the accelerated particles. This screen may consist of a metal plate coated with luminescent material (ZnS, MgO or Al_2O_3) or of a quartz disk. CsI crystals have been applied for very low currents. The coated metal plates can be produced in a simple

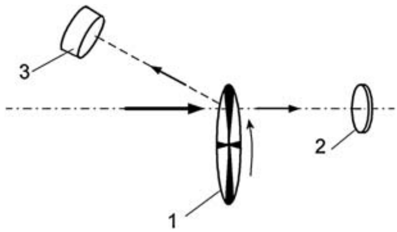

Fig. 15.5. Beam current measurement using ions backscattered from a rotating sector disk: 1, sector disk; 2, target; 3, particle detector

way, for example by moving a metal plate in the vapor of a burning piece of magnesium. An additional advantage is the electric conductivity of a metal plate. In contrast to insulating screens, no discharge effects appear on its surface that may be falsely interpreted as instabilities in the beam position. On the other hand, the lifetime of coated screens is limited, especially for MeV ions. Therefore, the most commonly applied material for beam observation screens is quartz. For suppression of discharge effects, the irradiated surface can be covered with a metallic net. Quartz emits a blue light under irradiation with ions and electrons. This can be observed directly through a glass window or in a remote mode by use of a TV camera. For higher beam power, the light emission changes to glow colors of red, yellow and white. Ion beams with such high beam power can be observed with quartz disks only for a short time to prevent damage to the material. At high beam power, the infrared radiation from a metallic plate in conjuction with a dedicated infrared-sensitive camera can be used for beam monitoring [3].

The main disadvantage of the observation screens mentioned above is the interruption of the beam. Therefore, in the FZ Rossendorf, a control method without complete beam interruption has been developed, and has been applied over a wide range. In accordance with the requirements of the experiments and the stabilizing circuits and to define the optical axis of the system, some slit devices are installed in the beam line of the electrostatic accelerator, especially at the entrance and exit of deflection magnets, in front of focusing lenses and at the places of beam crossovers. A small part of the beam intensity hits the slit plates. The electric signals from a 4-sector slit are amplified by a 4-channel preamplifier and 4-channel amplifier, both with adjustable gains, and are visually displayed in a 4-channel 10-element LED bar graph array (Fig. 15.6). Owing to the identical arrangements of the LED display and the slit devices, the accelerator staff get immediate information about the beam position and stability. The combination of these LED displays with retractable Faraday cups behind the slits has proved to be an effective piece of equipment for beam transport optimization in electrostatic accelerators.

Fig. 15.6. Beam diagnostic equipment at the Rossendorf 3 MV Tandetron: beam position monitoring by slit devices and LED display (*center*), NEC beam profile monitor (*left*), current measurement using retractable FC (*top*), and computer-controlled parameter variation (*foreground*)

15.4 Beam Profile Monitors

15.4.1 Beam Profiling by Sensing Wires

The position and intensity distribution inside an ion beam can be measured by a net of insulated thin wires [4]. The displayed current signals from each wire give information about the intensity distribution in the horizontal and vertical directions. This basic principle is modified in commercial beam profile monitors (BPMs) using a wire moving in two perpendicular directions through the cross section of the beam. Inside the BPM from NEC, Middleton, USA, a helical grounded wire is moved by a motor (Fig. 15.7, [2]). The rotation axis is arranged at 45° to the horizontal and vertical directions. The wire sweeps across the beam twice during each revolution to give a y-profile in one half-revolution and an x-profile during the next half-revolution. The secondary electrons generated on the wire are collected by a cylindrical electrode and give information on the beam intensity at the wire position.

Fig. 15.7. Principle of NEC beam profile measurement using rotating helical wire (Reprinted from [2], with permission from NEC)

The signal is displayed for both directions on an oscilloscope (see the oscilloscope on the left side of Fig. 15.6). A modified version of this BPM can be applied for very low currents (particles/s) [5]. Here, a solid-state detector collects counts from several turns of the wire. The signal is fed into an MCA card in a standard PC. The display is similar to the high-current mode. The emission of secondary electrons depends on the atomic mass number and energy of the accelerated ions. Using calibration measurements for different ions and energies, the signal of the BPM can also be used for beam current measurements.

Inside the BPM from HVEE, Amersfoort, Netherlands, a Y-shaped sensing wire sweeps through the beam. The scanner head is mounted at 45° to the horizontal beam axis [6]. The collected beam current from the scanning wire is displayed for the horizontal and vertical directions on an oscilloscope (Fig. 15.8), whose time base moves synchronously with the sweep of the scanner. The sweeping of the scanner is controlled by the drive electronics together with so-called power and reference coils interacting with permanent magnets at the base of the sensing wires. By installation of additional electrodes or by adding a positive bias voltage to the scanning wire to suppress secondary ions, the BPM can also be applied for beam current monitoring without dependence on the energy and atomic number. A potential-separated preamplifier with a 30 V bias potential has been applied in the BPM of the Rossendorf 5 MV tandem accelerator. This modification has proved to be helpful, especially in beam profile measurements for negative ions, where the secondary electrons can reduce or completely compensate the primary signal from the ion beam.

The displayed signals from both types of BPM are nearly identical; for the handling conditions also, no remarkable differences exist.

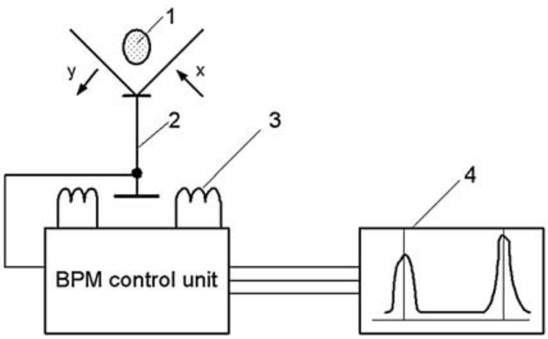

Fig. 15.8. Principle of HVEE beam profile measurement using scanning Y-shaped wire: 1, ion beam; 2, sensing wire; 3, power and reference coils; 4, oscilloscope

15.4.2 Beam Profiling Using Gas Ionization

At the cyclotron U-120 at the FZ Rossendorf, a BPM using residual-gas ionization was tested. It was manufactured in the RRC Kurchatov Institute, Moscow [7]. The electrons (or ions) generated in the residual gas by the ion beam are extracted by a transverse electric field (x-direction in Fig. 15.9). According to their transverse coordinate of generation in the electric field, the extracted electrons have different energies. After passing through a resolution slit and deflection by an electrostatic mirror, the electrons hit an electron–optical converter equipped with a channel-plate amplifier. The signals from the converter are displayed on a TV or PC monitor. In the y-direction, the electrons hit the converter according to the x-coordinate of ionization inside the extracting electric field; the perpendicular transverse coordinate y is not influenced by the electrostatic mirror. Consequently, both transverse coordinates of the detected electrons on the observation screen are a definite function of their generation points inside the beam cross section. Together with the measured vacuum in the beam line, the detected electron current also allows ion beam current monitoring. The resolution of this BPM would also allow its application to electrostatic accelerators.

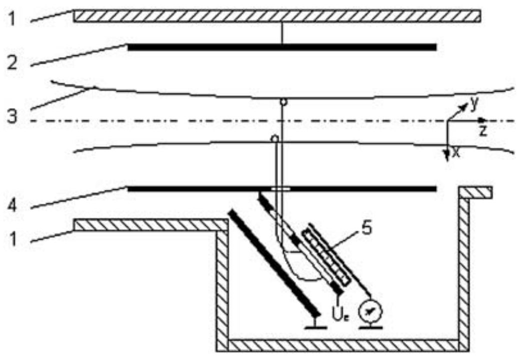

Fig. 15.9. Beam profile monitor using residual-gas ionization: 1, beam line wall; 2, grounded condenser plate; 3, ion beam; 4, extraction condenser plate connected to deflecting plate of electrostatic mirror; 5, channel-plate amplifier of electron–optical converter

15.5 Beam Stoppers and Safety Equipment

The Faraday cups installed in the beam line of an accelerator can be applied for beam current measurements and also to stop the beam during breaks in the experiment, as in the case of radiation hazards. In electrostatic tandem accelerators, the ion beam is preferably stopped with an FC in the injector region. Special considerations are necessary for accelerator operation near the maximum terminal voltage. A fast beam stop in the injector region causes an increased terminal voltage and may create a voltage breakdown with consequent damage to the accelerator. At the high-energy side of a tandem or in a single-stage accelerator some additional consideration, must be taken into account in the application of an FC for beam stopping owing to the higher beam power and possible nuclear reactions. The sputtering and heating effects of high-energy ion beams can damage the FC, and this results in a reduced accuracy of current measurements. Because beam stopping on the high-energy side does not interrupt the energy-stabilizing circuit, this method has been preferred by accelerator staff. Therefore, a dedicated cooled FC should be installed, which is able to stop all kinds of high-energy ion beams. At the Rossendorf 5 MV tandem accelerator, a radiation-cooled FC has been applied for this purpose. The stopper must consist of material with a high atomic number (e.g. tantalum), and the irradiated bottom should be exchangeable to prevent nuclear reactions. After long-time acceleration of Li ions, a beam stopper can create unexpectedly high neutron radiation during proton acceleration owing to the nuclear reaction ^{7}Li(p, n)^{7}Be.

For high-accuracy implantation experiments, a combination of fast electrostatic beam deflection and conventional beam stopping using a retractable FC has been advantageously applied. After the required implanted fluence has been reached, the ion beam is deflected outside the implantation chamber on to the wall of the beam line, and an FC before the beam-scanning system prevents the implantation of ions backscattered from the wall.

In the case of a radiation hazard, the safety equipment must stop the ion beam fast, reliably and completely. In tandem accelerators, this can be realized by a fast, pneumatically moved FC with an electronic interlock to prevent any unwanted retraction of the FC. Owing to the possible generation of radiation in a beam stopper, a retractable FC used for radiation safety purposes in the beam line of a single-stage accelerator must be combined with switching off the accelerating voltage.

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