9 Stabilization

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9.1 Introduction

One of the outstanding features of electrostatic accelerators is the low energy spread and the high energy stability of the beam. The low energy spread results from the fact that all particles emerging from the terminal at the same time are accelerated by the same voltage to the same energy. The residual energy spread arises from processes in the ion source and, in the case of a tandem accelerator, at the stripper. The purpose of the stabilization system is to keep the energy constant. The control loop should be efficient enough that the remaining fluctuations do not further degrade the energy resolution given by the above-mentioned energy spread and by the resolution of the experimental setup.

9.2 Principles of High-Voltage Generation and Stabilization

First of all, one has to maintain the accelerating voltage constant to achieve high beam energy stability. Fortunately, the properties of electrostatic machines facilitate a terminal voltage stabilization of the order of 10^{-5} to 10^{-4}. Moreover, one can modulate the voltage of energy-defining parts of the machine to achieve the highest stability.

9.2.1 Terminal Voltage Resulting from Currents and Impedance

In a machine without any stabilization system, the terminal voltage V_t results from charging and discharge currents acting on the terminal impedance according to (9.1), as shown in Fig. 9.1:

$$\frac{V_t}{R} + C_t \frac{dV_t}{dt} = I_{ch} - (I_{p+} - I_{p-} + I_{lost}) \tag{9.1}$$

Considering the Munich MP tandem as an example, the parameters are approximately $I_{ch} = 210\,\mu\text{A}$ ($\leq 600\,\mu\text{A}$), $I_{p+} + I_{p-} \leq 10\,\mu\text{A}$, $I_{lost} \leq 10\,\mu\text{A}$, $R = 60\ \text{G}\Omega$, $C_t = 500\,\text{pF}$, and $V_t = 12.5\,\text{MV}$ ($\leq 15\,\text{MV}$).

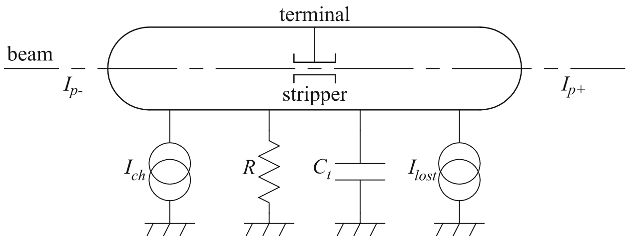

Fig. 9.1. Equivalent-circuit diagram of a tandem accelerator. I_{ch} is supplied by the charging system (the total of the up charge and, if existing, the down charge). I_{p-} is the beam current flowing from the ion source to the terminal; I_{p-} is negative. I_{p+} is the beam current flowing from the terminal to the high-energy end of the tandem. I_{lost} is the so-called lost current, mainly caused by tank gas ionization. R is the resistance of the voltage divider chains, column, and tube, if applicable. C_t is the terminal–tank capacitance

The sources of terminal voltage fluctuations are mainly the variation in the charging current, caused by inhomogeneity of the belt or the charging chains, but also fluctuations of the discharge current in the tank gas due to ionization by gamma radiation. Provided that the machine is in good shape, typical values of the voltage instability are of the order of 2 to 20 kV peak to peak. For short fluctuations, the voltage stability profits from the big time constant RC (several seconds). The terminal voltage cannot change rapidly if there are not catastrophic currents involved, as in the case of a spark. Long-term fluctuations, however, must be compensated for.

9.2.2 Basic Principle of Stabilization

Figure 9.2 shows the typical design of a stabilization system of a tandem accelerator. The main parts are a beam-energy-analyzing system, a generating voltmeter, a control amplifier, and a corona points assembly.

One cannot measure the terminal voltage with adequate accuracy by means of standard voltmeters. Therefore the beam energy is measured with a system consisting of a deflection magnet, a pair of slits, and a differential slit current amplifier. If the beam energy differs from the nominal value given by the field of the 90° magnet, the deflection angle of the magnet varies. This causes different beam currents at the slits and an error signal at the slit amplifier. Another method to measure the terminal voltage is electric-field measurement with a generating voltmeter (GVM) at the tank wall. This device works with a rotating electrode to chop the field and another electrode to pick up the current pulses, which then are rectified and amplified. The resulting signal is less accurate than the beam energy analysis described above, but in the absence of a measurable beam current it is the best choice. The best is to switch between the two modes automatically. If a beam current is present and the terminal voltage does not differ more than a given amount

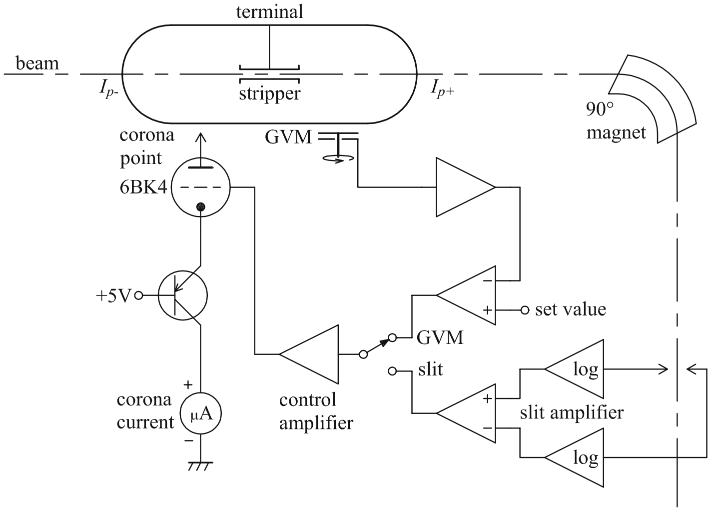

Fig. 9.2. Standard stabilization system of a tandem accelerator

(e.g. 10 kV) from the set value, slit control is used. Otherwise, if either no beam is present or the terminal voltage is too far off, so that one must suspect an unwanted beam, GVM control is applied.

The corona points produce a controlled corona discharge to compensate the fluctuations of the charging and discharging currents to and from the terminal. The assembly consists of some needles standing out of a grounded receptacle. This configuration acts as a triode, so that a swing of few kV applied to the needles is sufficient to control the corona current in the range of zero to 100 µA. The control voltage is supplied from an amplifier with a high-voltage vacuum tube as the output stage.

The energy-analyzing system, the amplifier, the corona points, and the terminal with its capacitance act as a feedback control system with nearly perfect integral characteristics: an energy deviation causes a proportional change of the corona current and, owing to the terminal capacitance, a corresponding ramp of the terminal voltage. Unfortunately, this ramp is delayed as a result of the slow building up of the corona discharge in the tank gas; this acts like a delay line with a propagation time of the order of 30 ms (in big machines) [1]. However, a feedback control system becomes unstable and starts to oscillate if the overall phase shift is 360° and the open-loop gain is greater than 1 at a given frequency. Owing to the intentionally negative feedback there is a phase shift of 180°, the integrator contributes 90°, and another 90° is added by the corona delay at a frequency of

$$f = \frac{1}{4T_d} \tag{9.2}$$

If the delay time T_d is 30 ms, the oscillation frequency will be 8.33 Hz.

To analyze the electrical behavior of the control loop, one can measure the response of the terminal voltage as a function of a signal applied to the grid of the corona tube. A proven method to get the frequency response is to apply sine wave voltages with variable frequencies to the grid of the corona tube and measure the amplitude and phase of the AC component of the terminal voltage using a well-calibrated capacitive pickup (described in Sect. 9.3.3). It is important that the amplitude is small enough to prevent saturation effects. On evaluating the data, one will find the corona delay time T_d and the terminal time constant $T_{RC} = R_t C_t$ (some hundreds of ms). R_t comprises the column resistance in parallel with the corona impedance. Since all other time constants in the system are comparatively small, the open-loop gain is given by

$$A_l = -A_0 \frac{e^{-pT_d}}{1 + pT_{RC}} \tag{9.3}$$

A_0, the DC gain of the system, is set to a maximum, so that oscillation does not arise yet. The condition for that is

$$A_0 < \left| 1 + i \frac{\pi T_{RC}}{2T_d} \right| \tag{9.4}$$

The reduction of the fluctuations by the control system is described by the control factor

$$F_c = 1 + \frac{A_0 e^{-pT_d}}{1 + pT_{RC}} \tag{9.5}$$

One can compensate the delay electronically only in a small frequency range, and there is nearly no benefit from that. Therefore, if the control factor of the corona control is too low to obtain sufficient stability, one must add a faster controlling element, e.g. stripper modulation or controlled down charge, as treated in Sects. 9.4.2 and 9.4.3.

9.3 Measuring System

One can determine the terminal voltage from column current measurement or from electric-field measurement by means of a generating voltmeter. Alternatively, one can use a beam-energy-analyzing system consisting of a deflection magnet and a beam-position-measuring device.

Because of the voltage and temperature dependence of the column resistors, the measurement of the column current is the least accurate approach. Moreover, it represents only the voltage of the outer column section. The generating voltmeter is much more accurate. If it is properly positioned, its output indicates the terminal voltage without significant interference from other parts of the machine. However, provided that a macroscopic ion beam exists, the best method is beam energy analysis, as described below. It is sensitive to the particle energy, which is the value to be stabilized. Energy deviations are indicated and corrected whatever their source may be. Examples are an instability of the injection energy, and the increasing energy loss in a stripper foil if the foil thickens during use. Energy analysis is more accurate than the other techniques and its response time is superior.

9.3.1 Energy-Analyzing System

The ion-optical components of the analyzing system are a quadrupole lens, the object slits, the magnet, and the image slits. The beam at the high-energy end of the accelerator is axially symmetric. The quadrupole doublet focuses it to an upright ellipse at the object slits. The small vertical divergence allows one to make the gap of the magnet small, and so to save energy. The magnet is usually a double-focusing 90° magnet with 26.5° shim angles, the object and image distances being twice the bending radius. The edges of the pole pieces are beveled in an approximate Rogowsky profile to avoid saturation effects, which would result in a field-dependent beam path. The field must be highly stable, since it is the measure of the energy. A closed-loop field control system provided with an NMR teslameter is capable of keeping it constant within 10^{-5}. The energy dispersion of the magnet combined with the drift space to the image waist is

$$\frac{\Delta x}{\Delta E/E} = 0.5\left\{R(1-\cos\alpha) + D\left[\sin\beta_2 + \frac{\sin(\alpha-\beta_2)}{\cos\beta_2}\right]\right\} \tag{9.6}$$

where R is the bending radius, α the deflection angle, β_2 the exit shim angle, and D the image distance. For a double-focusing 90° magnet, (9.6) reduces to

$$\frac{\Delta x}{\Delta E/E} = 2R \tag{9.7}$$

An energy deviation $\Delta E/E$ of only 10^{-5} typically produces a beam offset Δx of the order of 5% of the horizontal spot size at the image slits.

The slits collect a small fraction of the beam current only, from the rim of the beam. To obtain an output signal proportional to the beam offset, independent of the beam intensity, one has to use logarithmic current-sensitive amplifiers and subtract their output voltages. The current range of the amplifiers must be very wide, and the frequency response must be fast compared with the other components of the control loop. A logarithmic converter, made as usual with a transistor in the feedback path of an operational amplifier, is rather slow at a low input current. This can be overcome by piecewise logarithmizing and subsequently adding the pieces [2, 3] or by digital logarithmic conversion using a signal processor. In any case, the operational amplifier of the input stage must be excellent with respect to bias current, input offset voltage, and drift.

Assuming a normal distribution of the current density (approximately exponential in the tails), the response of the logarithmic amplifiers to the beam offset is linear to a first approximation. This is an important property of the control loop, which applies only if no secondary electrons from one slit electrode hit the other one. The electrons can be suppressed by an electric field, generated by a bias voltage from a battery. Also, the shape of the electrodes must be adequate: sharp edges are better than cylindrical electrodes. Staggered slits with the two electrodes at different positions in the beam direction can also help to avoid secondary electrons from one slit hitting the other one.

There is one more source of error in the slit signal. In some cases, for example if negative molecular ions are injected into a tandem, a mixture of various particles with different charge states is accelerated in the high-energy section. If the magnetic rigidity of unwanted particles is very close to that of the wanted particles, they can hit one of the slit electrodes and so affect the control signal. A remedy can be so-called shadow slits, a slit pair installed upstream.

Although the accuracy and the reproducibility of the analyzing system described above are excellent, the absolute value of the beam energy can be calculated only roughly from the magnet data, because the magnetic field along the beam path, including the fringing fields of the magnet, is not exactly known. A standard method for calibration uses reactions with well-known resonances, such as the excitation functions for elastic and inelastic scattering of ^{12}C(p, p)^{12}C and ^{12}C(p, p$'$)^{12}C at the resonance at 14.233 MeV [4]. If a spectrograph is available, one can use it to compare the magnetic rigidity of ions from the accelerator with that of 8.784 MeV α-particles from the decay of ^{212}Po [5]. Also, a direct measurement of the time of flight of a chopped beam over a carefully measured distance has been performed [6].

9.3.2 Generating Voltmeter

For some experiments, for example in accelerator mass spectroscopy, the terminal voltage must be stabilized even in the absence of a measurable beam. In this case a generating voltmeter (GVM) is the most accurate tool for voltage measurement and stabilization.

The generating voltmeter, called there the *Feldmühle*, was first described by Lueder and Schwenkhagen [7] and used to measure the electric field in the atmosphere at the earth's surface. In the accelerator, it is destined to measure the electric field caused by the terminal voltage. Usually the GVM is mounted very close to the tank wall in a position opposite to the terminal, where the field is determined only by the terminal voltage, and as far as possible from the corona points. The generating voltmeter (Fig. 9.3) consists of a grounded rotating disk with apertures to chop the electric field, and isolated static electrodes delivering alternating current pulses proportional to the field. The rotating plate covers and uncovers the signal plates alternately so that, owing

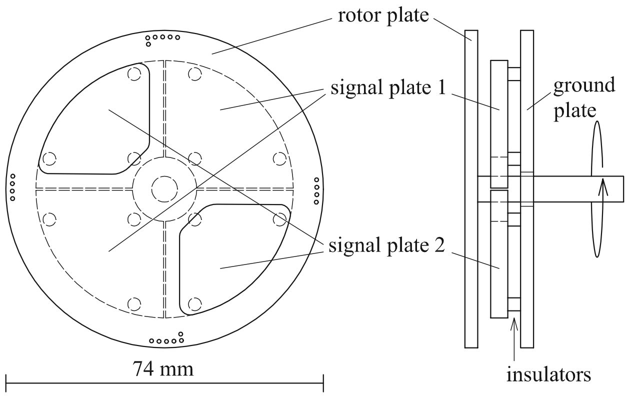

Fig. 9.3. Generating voltmeter (GVM)

to the alternating field, a current is induced in the signal plates. This current I follows the equation

$$I = V_t \frac{dC}{dt} \tag{9.8}$$

where the terminal voltage is V_t and the time-dependent capacitance between the signal plate and the terminal is C (C_1 or C_2 in Fig. 9.4). If the opening in the rotating plate has exactly the same size and form as the static signal plates, the waveform of the capacitance looks like a triangle (to a first approximation). Therefore the alternating current has a rectangular pulse form with a rather high slew rate. This causes some problems in the signal processing.

An essential improvement in the design is to use two sets of signal plates and to make the windows in the rotating plate smaller than the area of the signal plates. In this case the rotating plate covers more than the area of one signal plate, resulting in capacitances C_1 and C_2 as shown in Fig. 9.4. Therefore the readout signal (I_1 and I_2 in Fig. 9.4) is shaped in such a way that its derivative is zero at the zero-crossing (every 90°). So the readout electronics can be slow, and there is enough time to control the electronic switches.

Position holes in the rotating plate are read out by two photologic sensors to control the analog circuit shown in Fig. 9.5 via a state machine. Two index holes are used to start the phase-controlled rectifier for each 180° again. This allows one to determine the polarity of the electric field. In the first phase, from 0° to 90° in Fig. 9.4, I_1 is integrated in A_1, and I_2 is integrated in A_2. The results are sampled in the sample-and-hold gates A_3 and A_4. In the next phase, I_1 is integrated in A_2 and I_2 in A_1. This procedure is continuously repeated. The timescale for 90° is 20 ms, corresponding to the 50 Hz mains frequency, to suppress interference from the line voltage. The difference between the samples, obtained by the subtracting amplifier A_5,

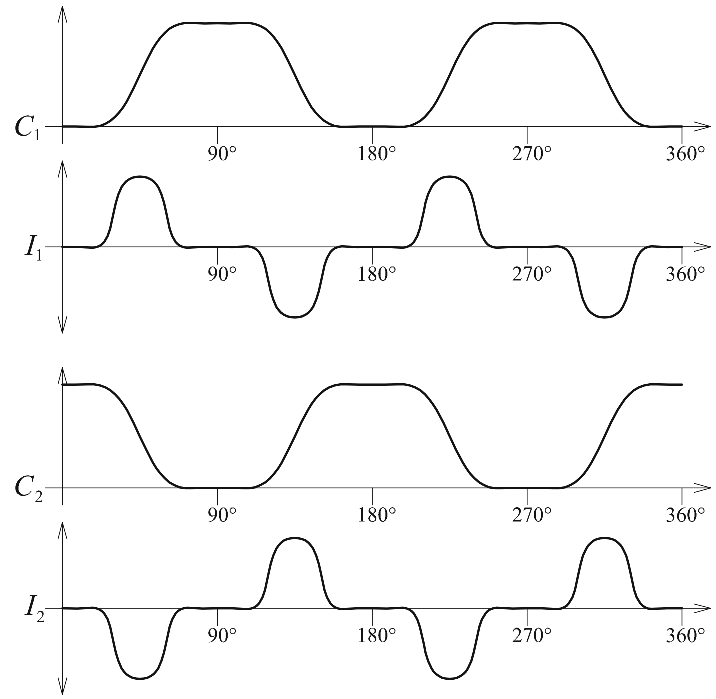

Fig. 9.4. Capacitances of the signal plates to the terminal, and currents, as a function of time

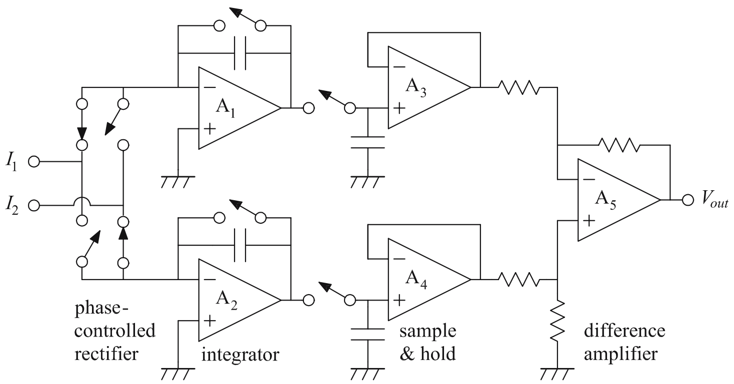

Fig. 9.5. Circuit diagram of the generating-voltmeter amplifier

represents the actual value of the terminal voltage, and common-mode noise is suppressed.

A few details are important for the accuracy of the GVM. The motor axle has to be grounded via a well-conducting collector. An approved combination is silver-graphite brushes on a highly polished stainless steel collector ring.

The insulators of the signal plates must be hidden from the surface, so that charge possibly sitting on the insulators cannot affect the signal (no printed circuit boards as signal plates!). The rotor and the stator plates should be polished, and have to be kept clean. Otherwise, an isolating film may cover the electrodes, where parasitic charge deposit may occur. The accuracy of the measurement is better than 10^{-4}.

9.3.3 Capacitive Pickup

The ripple of the terminal voltage can be measured with a capacitive pickup (CPU). This is an electrode at the tank wall connected to a current integrator. Since the electrode current is proportional to the derivative of the terminal voltage, the output of the integrator represents the AC component of the terminal voltage. An RC high-pass filter at the input of the integrator is necessary to avoid saturation of the operational amplifier by the ionization current flowing to the pickup electrode.

The CPU signal is usually displayed on an oscilloscope, acting as a monitor for the ripple. Since it is contaminated by ionization current fluctuations, it is not advisable to feed it into the control loop. This may deteriorate the voltage stability instead of improving it. An exceptional case might be the generating-voltmeter control mode if the GVM response is very slow.

9.4 Final Control Elements

The first control element for a stable terminal voltage is the charging system. Since the response of the terminal voltage to up-charge current changes is very slow, one cannot include it directly into the control system. But a uniform up charge is most important for terminal voltage stability. The most commonly used control element is a controlled corona discharge, which acts much faster. The ion transit time from the corona dominates the closed-loop behavior of most stabilizing systems. Even faster final control elements, e.g. controlled down charge [8] or stripper modulation [9], can further improve it.

9.4.1 Controlled Corona Discharge

As described in Sect. 9.2.1, in an electrostatic accelerator without any stabilizing system the terminal voltage results from an equilibrium of the charging and discharging currents in the terminal impedance. A controlled corona discharge system acts as an additional shunt load. Considering the Munich MP tandem as an example, the operating current of the shunt circuit is $50\,\mu A$, and therefore it has a range of zero to $100\,\mu A$. As shown in Fig. 9.6, the corona assembly consists of an insulated set of 12 needles standing out of a grounded mushroom. The needles are directly connected to the anode of

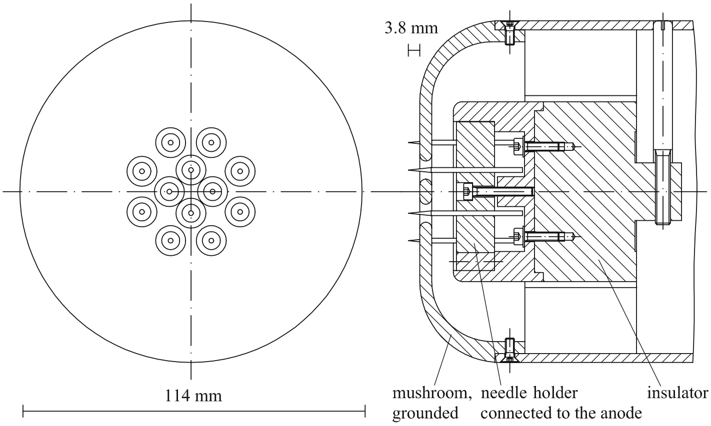

Fig. 9.6. Design of a corona needle assembly

a high-voltage vacuum tube. The grid of the high-voltage vacuum tube is driven by the output voltage of the control amplifier.

A linear positioning drive controls the distance of the corona assembly from the terminal with respect to the operating point of the stabilizing system. The higher the terminal voltage, the higher must be the distance from the terminal so that the field strength at the needles is always the same. Then all other parameters of the stabilizing system remain constant.

9.4.2 Controlled Down Charge

As mentioned above, the response of the terminal voltage to changes in the up-charge current is very slow. The calculation of the transfer function is difficult owing to the complex geometry of the accelerator structure. But the simple equivalent-circuit diagram in Fig. 9.7 shows the basics. Let us assume that a concentrated positive charge Q (on a small piece of the belt or a pellet of the chain) is moved from ground potential to the terminal. C_q is the capacitance of the charge carrier to ground, C_t the terminal capacitance to ground, and C_{qt} the capacitance of the charge carrier to the terminal. The terminal-voltage change is given by

$$\Delta V_t = Q \frac{C_{qt}}{C_q C_{qt} + C_q C_t + C_{qt} C_t} \tag{9.9}$$

When the charge carrier is on its way from ground to the terminal, C_{qt} is very small compared with C_t, and there is nearly no terminal-voltage change for many hundreds of ms. Only if the charge is very close to the terminal does C_{qt} reach the order of magnitude of C_t, and a voltage step occurs. The long delay is not tolerable in a closed loop. But if we reverse the motion and the polarity, and let the charge carrier travel from the terminal to ground,

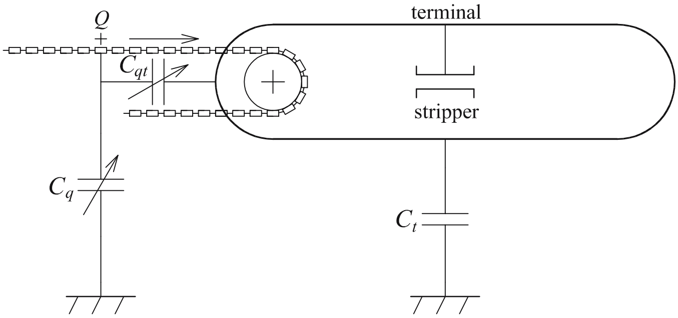

Fig. 9.7. Equivalent circuit for the charge transport

the charge leaving the terminal induces an immediate change of the voltage. Hence, a controlled down charge can be a faster control element than a corona discharge.

The actual charging device in the terminal is similar to the up-charge device at ground potential. In the case of a belt charging system, it is a screen spraying charge on the belt. The charge is supplied by a controlled current source. If the charging system is a chain or a ladder, the existing inductors in the terminal, which normally are connected to pickup wheels, must be supplied from controlled voltage sources, a positive and a negative one. The position of the charging electrodes must be as close as possible to the end of the terminal, so that the travel time of the charge inside the terminal is as short as possible. But even if the assembly is designed very well, a delay of 10 ms or more is inevitable, and this limits the control factor of the loop. A data link is necessary to transmit the control signal for the down-charge power supply from ground potential to the terminal. The transmission delay of this link should be small compared with the delay mentioned above to avoid further performance degradation.

9.4.3 Modulation of the Effective Accelerating Voltage

Since the signal delay characterizing the corona transfer function and, to a minor degree, also the response of down-charge systems, is the worst property of the control loop, a more direct control element for the effective accelerating voltage is desirable. One would like to apply directly a corrective voltage, derived from the error signal, to an energy-affecting element. The most suitable device for this purpose is a bipolar controlled current source, capable of a few kV output voltage. The voltage is determined by the current, integrated by the load's capacitance with an optional capacitor connected in parallel. In this way, a stable integral action of the control loop is achieved. It should be noted that a closed loop is possible only in the slit control mode. The GVM signal cannot be used, because it does not indicate the effect of a directly applied corrective voltage.

Points to be considered for the application of the corrective voltage are the ion injector, the high-voltage terminal or the stripper, and also the target of the beam. The latter can be neglected for two reasons. First, it is difficult to insulate the target with the complete experimental setup and to attach high voltage to it. Secondly, the effective energy cannot be measured, and no signal is available to be applied to the control loop.

To modulate the energy of the injected beam, one must apply the corrective voltage to the injector, that is, the ion source with all ion-optic elements and the associated power supplies. If the injector is already insulated and connected to a preacceleration voltage, the corrective source, controlled through a fast data link, can be inserted between the preacceleration power supply and the ion injector. A disadvantage of this method is interference to the ion optics at the low-energy end of the accelerator, due to the fluctuating injection energy. Particularly, if a buncher for a nanosecond pulsing system is installed between the injector and the accelerator, this technique is not applicable.

Modulating the terminal stripper of a tandem accelerator is much better in this respect. At the terminal, the particle energy is so high that a few kV energy modulation does not influence the optics of the high-energy tube. A further advantage of this method is that the corrective voltage acts in a way that is amplified according to the charge state of the ions. The technique is as described above: a bipolar current source controlled from the error signal via a fast data link is connected to the stripper. Only a few practical aspects must be considered. The stripper foils must be protected with a shield connected to the stripper to prevent rupture by electrostatic forces. If a gas stripper is used, one must bear in mind that the gas pressure in the pipe between the needle valve and the stripper tube is in a region where gas discharges occur even at moderate voltages. Therefore the needle valve must be connected to the stripper, and the pipe must be metallic.

Another successful method to apply the corrective voltage to the terminal has been realized at the Munich MP tandem [2]. An insulated electrode, the so-called liner, covering a part of the inner tank wall is connected to a bipolar current source controlled by the error signal. The voltage at the liner results from the current integrated by the liner capacitance. A fraction of this voltage, determined by the capacitances of the terminal to the liner and to the grounded tank wall, is induced at the terminal. Since this fraction is only about 20%, the source must be capable of $\pm 20\,\mathrm{kV}$, so that the corrective voltage at the terminal is $\pm 4\,\mathrm{kV}$. The most serious problem of this technique is damage by tank sparks. Since the liner is directly exposed to sparks the destructive energy is high, and it is difficult to protect the liner, the tank feedthrough, and the electronics adequately.

9.5 Functional Specification of an Ideal Stabilizing System

For many accelerator installations, a standard stabilizing system as described in Sect. 9.2.2 is sufficient. If the charging system is in good shape, the voltage fluctuations of the free-running machine are only a few kV, and this can be reduced to below 1 kV FWHM using the standard technique.

Bare corona stabilization may be insufficient if either precision experiments require an extra-stable beam energy or the stability of the free-running machine is poor and cannot be further improved. In this case stripper modulation is the best choice. One can implement it even in an existing machine, provided that the stripper can be insulated. However, the voltage span of the corrective power supply does not cover the whole control range. Therefore a corona loop or a down-charge loop is still necessary to keep the stripper modulation voltage around zero. In most cases the operator controls the up-charge current by hand. This is due to the slow response of the charging system. But, under computer control, one could mix a suitable control signal using the terminal-voltage set value and the actual value of the corona current (or the down-charge current if this is part of a control loop). In any case, it is important to avoid saturation of amplifiers and power supplies in all loops, otherwise the system tends to oscillate, even if the overall gain is set to an optimum for small signals.

Although one can reduce the terminal-voltage fluctuations to about 200 V FWHM using the techniques described above, the actual accuracy of the particle energy at the target does not correspond to this value. There are some more energy-deteriorating effects. The thermal motion of the particles in the ion source contributes 20 to 200 eV FWHM. The stripper-induced energy spread, including straggling and stripper inhomogeneity, is between 100 eV for light ions in a gas stripper and about 40 keV FWHM for heavy ions in a foil stripper. Injecting negative molecular ions and breaking the chemical bond in the stripper foil yields even higher energy straggling. Owing to the target thickness, one has to take into account similar values to those for the foil stripper. Hence, sophisticated stabilization techniques are most useful for precision experiments with light-ion beams. In the case of heavy ions, effects besides the terminal-voltage stability dominate the overall characteristics.

For the routine operation of an accelerator, the aspects of usability are very important. The operator must be able to set up the machine quickly for a new beam. The best tool for that is a computer control system, with data tables and algorithms included to determine the operating conditions and to set the values with adequate timing. So, the control system can adjust the position of the corona points, gradually set the charging current with the actual terminal voltage in check, and then hand over the control to the GVM stabilizer. With the stabilizing system in operation and the terminal voltage close to its set value, the charging current must be readjusted so that the corona current is around the nominal operating point (e.g. 50 μA). This is necessary also if the beam is injected, and can be done by the operator or by a control computer as well. Also, the position of the corona points has to be readjusted so that the control amplifier output is around zero.

Simultaneously, the analyzing-magnet current is set, and the NMR is switched into search mode. If the NMR signal is present, the system is switched into field-stabilizing mode. All ion-optic elements are to be preset, too.

The following steps may be taken with or without a computer algorithm. The beam is injected and optimized up to the object slits and then forwarded to the image slits. Possibly one will have to slightly modify the terminal voltage to find it there. Now, the automatic switching mode of the stabilizer described in Sect. 9.2.2 can be activated. In this mode, the terminal voltage is controlled by the slit signal if a slit current is available and the voltage is not too far from the set value; otherwise, the GVM signal is used. So the machine remains close to its operating parameters even if the beam drops for a moment, and returns to normal operation when the beam is back. Catching a different charge state or particle is prevented by the condition for slit stabilization that the voltage is close to the set value. The last step in setting up the stabilizer is to optimize the loop gain. Starting from a fairly low value, the operator increases the gain until the system oscillates. This can be easily observed at the oscilloscope showing the capacitive-pickup signal. If no oscillation occurs, even with the gain set to its maximum, the system is not in good shape, and one should try to find the reason for that (e.g. poor focusing of the beam at the slits). Otherwise, the gain should be reduced until the oscillation stops. So the system is adjusted to yield optimal beam energy stability.

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