10 Stripper Systems

D. Weisser

Research School of Physical Sciences and Engineering, Australian National University, Canberra, Australia
david.weisser@anu.edu.au

10.1 Introduction

The stripping process, that is, changing the injected negative ions into positive ions, is the defining feature of acceleration in a tandem accelerator. However, it also results in loss of beam transmission efficiency and voltage-holding ability. Charge state fractionation, described in Box 5, and scattering reduce the beam intensity. How the latter also compromises the accelerator's reliable maximum voltage is explained in Sect. 10.2. Since the vacuum in the accelerator tube also affects the transmission, methods to achieve low pressure have been pursued over the years, leading to improvement of pumping systems, which is discussed in Sect. 10.3.

There are two choices of stripping media, gas and carbon foils. If stable beam transmission is the priority, then gas stripping is chosen. Gas stripper apparatus is described in Sect. 10.4. Gas stripping is also preferred for injected molecular beams and to enhance the population of low charge states. If, however, beam energy is the priority, then foil stripping is preferred at the expense of transmission efficiency and unvarying intensity. Box 6 surveys the manufacture of carbon foils, and Sect. 10.5 deals with foil stripping and failure modes. The short foil lifetimes for heavy ions limit the application of foil stripping to low- and medium-mass ions and to low-intensity applications.

In the pursuit of the highest energy from a given accelerator, further foil stripping within the accelerator, described in Sect. 10.6, provides additional substantial energy gains but with a sacrifice of intensity and machine stability. In Sect. 10.7, we canvass the need to select charge states in the terminal and how selection impacts on double-stripping operation. Methods are described to prevent undesired charge states from compromising the performance of the accelerator.

The last section deals with the use of strippers external to the tandem in laboratories with postaccelerators. The energy gain from the postaccelerator will be maximized if an external carbon stripper is used to produce higher charge states than those achievable even with a second stripper in the tandem.

The strength of heavy-ion tandem accelerator facilities is their flexibility. Being able to choose either gas or foil terminal stripping enhances flexibility, as does the option of a second stripper in the high-energy tube. These

stripping choices have demonstrated an extremely useful range of beam energies and intensities that have underpinned heavy-ion nuclear-physics research.

10.2 Interactions of the Beam with Stripper Material and Gas

By definition, tandem acceleration requires the stripping in the terminal of electrons from the injected beam. The choice of gas or a foil stripper has vacuum, beam transmission and voltage-holding consequences.

10.2.1 Interactions Between the Beam and Residual Gas

Too much gas in the accelerator tubes, from whatever source, causes trouble even for light beams. The slow-moving injected beam is readily disrupted by interaction with the gas through scattering and the production of neutrals, positive ions and electrons. This also affects positive ions in the high-energy tube, though to a lesser degree because they are moving faster. The electrons, neutrals, and positive and negative ions strike accelerator tube electrodes, producing more positive and negative ions, neutrals, electrons and even puffs of gas. These processes, at their most benign, cause dips in the voltage at the affected electrodes. If the voltage quickly recovers and the machine does not spark, this sequence is called conditioning, because the surfaces involved appear to be "cleaned", allowing further increases in voltage. If the ion and electron currents are too large, the gradient will be upset enough to cause the machine to spark.

But it is the electrons, produced by all these processes that are the immediate enemy. A runaway situation rapidly develops if the electrons are not steered into a tube electrode before they gain enough energy to create, upon collision, more than one electron and/or ion. The X-rays from these electron strikes ionize the insulating gas outside the tube, allowing charge to be drawn from the rings and the terminal to the tank wall and so dragging down the voltage by many MV. This process is *electron loading*.

Although too much gas in the tubes causes voltage-holding problems, small amounts, up to a pressure of 10^{-4} Pa, has little voltage impact and some benefit. This by-product of gas stripper operation helps quench secondary-ion currents and consequently the electron loading. This was a necessary ingredient for the successful operation of the straight-field accelerator tubes that preceded ones with inclined fields (Chap. 8).

10.2.2 Intensity Losses and Energy Sharing

Intensity losses in stripping are caused by three main mechanisms: charge state fractionation; multiple scattering, spreading the beam entering the

high-energy tube; and the Coulomb explosion of molecular ions, which can drastically increase the angular divergence of the beam as well as increase its energy spread.

10.2.3 Multiple Scattering

The stripping process intrinsically involves multiple small-angle scatterings, which spread the beam, making its angular emittance larger than the angular acceptance of the high-energy accelerator tube [1]. For gas strippers, because they can be adjusted to have fewer atoms per unit area than foils, the increase in divergence is quite manageable. A lens between the stripper foil and the entrance to the high-energy tube mitigates this problem by capturing scattered beam and focusing it through the high-energy tube (Sect. 10.7).

10.2.4 Molecular Beams

Cesium bombardment sputter sources produce negligible atomic negative-ion beams of elements with low electron affinity such as beryllium, nitrogen, calcium and magnesium. But they do provide useful intensities of their hydrides, oxides and carbides [2]. Although the molecules are readily dissociated in the stripper, this process and associated electron stripping inevitably result in losses of intensity and spreading of the beam energy, as described below.

The energy gained by a molecule in being accelerated to the terminal is shared among the constituent atoms. For the CN^- molecule, for instance, the nitrogen leaving the stripper has 14/26 of the incident energy, thus reducing the final available energy of the nitrogen beam. The lower N energy at the terminal also results in less population in the higher charge states, further reducing the beam energy available. That is why experimenters wanting the highest energy will opt to inject NH^- instead, where the N retains 14/15 of the incident energy.

The sharing of the low-energy acceleration is not the only debilitating factor. Worse still is the divergence increase caused by Coulomb explosion [3]. As a molecule traverses a stripper foil, several electrons are almost instantaneously removed, leaving the suddenly positively charged constituent atoms dissociated but still very close together. Their mutual Coulomb repulsion produces a substantial angle between them as they leave the foil on their way to the high-energy tube. Conservation of momentum says that the heavier constituent remains closer to the axis than the lighter one. But even the N on the axis have debilities, since those emitted in the direction of the beam gain energy from the Coulomb field, while those emitted opposite to the beam direction will have less energy. The energy change is less for the heavier constituent. Thus the Coulomb explosion effect for N in CN^- is much more severe than for N in NH^- in terms of both angular and energy spreads. There is a preference, therefore, to choose molecules in which the atom of interest is bound to the lightest possible partners.

Using a gas stripper to dissociate the molecule can minimize the effect of Coulomb explosion. As a molecular ion travels through a gas, the electrons binding it are removed, allowing the first neutral atoms and then low-charge-state positive ions to move well apart before their charge states, and therefore the Coulomb field, become high. For those beams that can only be adequately produced as molecules, using gas first to dissociate the molecule and then foil to produce a higher charge state is the preferred technique.

10.3 The Vacuum in the Tubes

The transmission efficiency of the accelerator is reduced if the vacuum in the accelerator tubes is poor. The quality of the vacuum depends upon the outgassing properties of the tubes, the speed and location of the pumps, and any gas introduced by the stripping equipment.

10.3.1 Vacuum Pumps

As mentioned in Sect. 10.2, a small amount of stripper gas was useful for old-fashioned straight-field tubes to reduce electron loading. However, even a small amount of gas has negative effects on beam transmission if not on voltage-holding ability. The advent of inclined-field tubes and magnetically suppressed ones, which sharply reduce electron loading, obviated the need to quench ions with stripper gas in the tubes. Therefore, the opportunity arose to reduce the residual negative effects of gas in the tubes by improving the vacuum. The main pumps at the ends of the machines progressed from mercury diffusion pumps with cold traps to low-backstreaming oil diffusion pumps, to ion pumps, to turbopumps and to cryopumps as each type became available. The vacuum, measured just outside the accelerator over the pump, ranged from $\sim 10^{-4}$ Pa, in the early days, to $\sim 10^{-6}$ Pa, as pumps got bigger and better.

In longer machines, the low pumping conductance of the accelerator tubes themselves, ~ 25 l/s for a 1.8 m long tube, vitiates the improvement in base pressure at the pumps. To place pumps in machines that were not designed with space and electric power for them proved a continuing challenge. At first, pumps were installed in the terminal to capture the stripper gas. This will be described in Sect. 10.4. Although having pumps capable of hundreds of liters per second at the ends of the machine and in the terminal helped, it was necessary to reduce the pressure in the tubes themselves, especially in longer machines. Additional ion pumps were installed in the dead sections where accelerator tubes joined, and rotating shafts were grafted into the columns to provide power. Figure 10.1 shows the ion pumps squeezed into the dead sections in the MP accelerator at Brookhaven National Laboratory [4]. A combined titanium sublimation and ion pump was added between units 6 and 7 in the Australian National University 14UD [5] and at four locations in

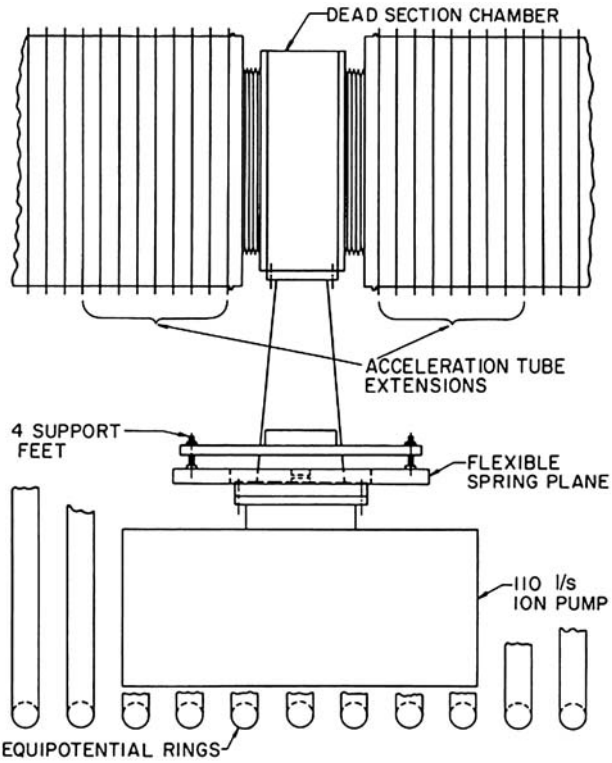

Fig. 10.1. Brookhaven National Laboratory dead-section pump (Reprinted from [4], copyright 1984, with permission from Elsevier)

the 25URC at Oak Ridge National Laboratory [6], shown in Fig. 10.2. This distributed pumping spreads the improved pressure throughout the path of the beam, greatly reducing beam–gas interactions.

The better pumps not only provide better vacuum but also inject fewer hydrocarbon contaminants into the tube. Hydrocarbons on electrode surfaces are potent sources of secondary ions, neutrals, electrons and gas, which, if present in sufficient quantity, cannot be conditioned away.

NEC led the way in reducing electrode contamination because their straight-field accelerating tubes are not very tolerant of strong electron sources. Their tubes are constructed using titanium diffusion-bonded to ceramic insulators instead of the polyvinyl acetate adhesive used to bond other tubes. To further reduce hydrocarbons, NEC also insisted on all-metal vacuum systems employing aluminum or copper gaskets, and titanium sublimation pumps coupled to ionizing pumps. However, some hydrocarbon contamination occurred while the accelerator tubes were being pumped from atmospheric pressure to $\sim 0.1\,\mathrm{Pa}$ since oil-sealed rotary pumps were used.

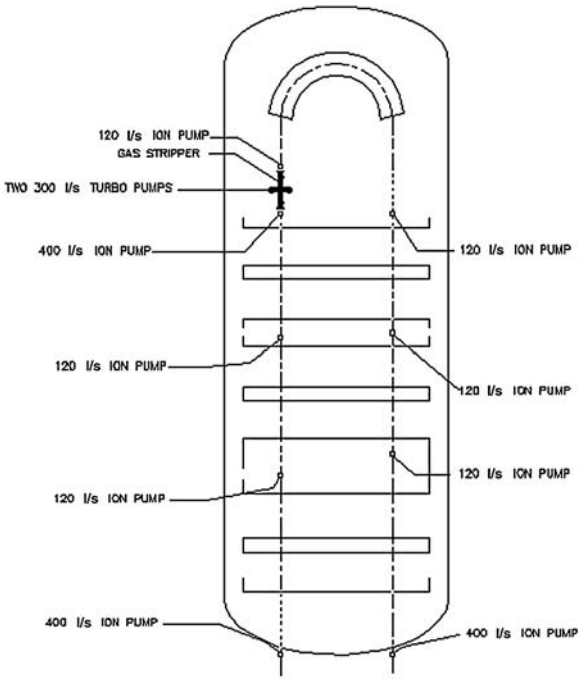

Fig. 10.2. Distributed pumping in the 25URC at Oak Ridge National Laboratory

This was in spite of employing liquid-nitrogen traps. The hydrocarbons were readily seen in residual-gas spectra. As experience with NEC machines increased, Viton O-rings were allowed, as were turbopumps, without noticeable deterioration in high-voltage performance. Whatever minor hydrocarbon contamination these introduced was readily conditioned away, allowing the tubes to perform at and above their voltage specifications.

10.4 Gas Stripping

The goal of the gas stripping apparatus in the terminal of a tandem is to present 1 to $2\,\mu g/cm^2$ of gas to the negative-ion beam, while minimizing the gas entering the accelerating tubes. In the simplest systems, which are adequate for light ions, gas is introduced into the middle of a canal, often ~ 8 mm in diameter and ~ 800 mm long. The gas exiting from the ends of the canal is restricted from going into the low-energy tube by a low-conductance section. This keeps the pressure in the low-energy tube low enough not to degrade the slow-moving injected negative ions, since the gas is preferentially pumped away via the high-energy tube. This solution is adequate for light ions and/or small accelerators, where the reasonable pumping impedance of the tubes allows the tube pressure to be adequately low.

10.4.1 Stripping Light Ions with Gas

Stripping is usually thought of as changing negative ions into positive ones, though, before the advent of the negative-helium-ion source, neutral 500 keV helium atoms were injected and then were stripped to positive using a terminal gas stripper. Early nuclear physics research using injected negative ions concentrated on light beams – hydrogen and helium isotopes. For these, gas stripping produced essentially 100% singly charged hydrogen and doubly charged helium.

There are rare situations when charge states lower than the most probable one are required. This is the case when the beam optics of the accelerator require that the terminal voltage for best beam transmission be near the design maximum. The desired beam energy is achieved by using a low charge state and the higher terminal voltage. For example, with 10 MV on the terminal and the gas stripper pressure set for equilibrium stripping, ^{12}C will have negligible intensity in the 2^+ charge state. However, if the gas stripper pressure is reduced to ∼20% of the equilibrium value, then the 2^+ beam will have 40% of the total intensity.

10.4.2 Design Geometry

The crucial design parameter of a gas stripping system is the diameter of the stripper canal. In order for the canal not to interfere with beam transmission, its diameter must be large. Since the beam reaching the terminal generally has a low divergence, the canal length is less crucial, though the restricted terminal size limits the length of the canal. These geometry choices conflict with the goal of minimizing the gas flow to keep the pressure in the tubes low, since the conductance of the canal goes as d^3/l, where d is the canal diameter and l its length [7]. In machines primarily servicing nuclear-physics needs, the canal is often ∼8 mm in diameter and 400 to 800 mm long. In accelerators optimized for accelerator mass spectrometry, where even small changes in transmission cause problems, canals are ∼11 mm in diameter.

10.4.3 Terminal Vacuum Pumps for Gas Strippers

Various types of pumps have been used in the terminal to pump away the stripper gas exiting the canal. Ion pumps do not have the capacity to deal with the gas load, so titanium sublimation pumps were used but suffer limited lifetimes and time-varying pumping speed. Cryopumps have been used but need periodic reactivation, usually passing the gas load through the accelerating tubes. The helium compressors for the cryopumps present further challenges, since either they must be housed in the terminal or the helium gas must travel to the terminal via insulating tubing from a ground-based compressor [8]. An alternative to pumps that trap the gas is to use a turbopump to capture and then recirculate the gas back into the center of the canal [9]. Further reduction in pressure in the tubes is achievable by pumping the

gas that escapes through a low-conductance section from the turbopumped region. This differential-pumping [10, 11] solution is described in the next section, describing a typical modern gas stripper system.

Turbopumps in high-pressure, high-voltage terminals are not without problems. The most serious is the susceptibility of their power supplies to spark damage. This problem can be overcome by eliminating the power supplies by operating the pumps directly from the 400 Hz terminal alternator. This results in the pump running at about half its nominal rotational speed, with the consequent reduction in pumping efficiency. The reduction is a manageable burden on the vacuum design and has the advantage of prolonging the lifetime of the pump bearings. An electronics-free option is to use an SF_6 gas turbine to drive the pump instead of an electric motor [12]. In any case the turbopump must be modified to operate in a high-pressure environment, of 0.7 to 1.55 MPa.

Even with turbopumps employing ceramic bearings lubricated with very low-vapor-pressure grease, there is a significant hydrocarbon component in the pump backing line and thus into the stripper gas input, causing a base pressure of ∼1.3 Pa. Since the pressure at the center of the canal may need to be less than that for molecular dissociation and for optimizing low charge states, an oil trap is required.

10.4.4 A Typical Modern Gas Stripping System

The stripper gas employed in most laboratories is either oxygen or nitrogen. Argon gas strippers are used, especially in AMS laboratories [13], to enhance high charge states where minimal noble gas gets to any ion pumps used. Typical features of a modern recirculating, differentially pumped gas stripper system are illustrated by the gas stripper in the ANU accelerator shown in Fig. 10.3 [11]. A pressure of 2.6 Pa of oxygen at the center of an 850 mm long canal will produce an integrated gas thickness, assuming a linear pressure profile, of $\sim 2\,\mu g/cm^2$. Since the beam diameter at the terminal is ∼3 mm, based on the beam spot observed on stripper foils, 8 mm was chosen for the diameter of the stripper canal itself, as well as for the low-conductance sections.

The stripper thickness is controlled with a valve that injects some gas into the turbo backing line to make up for gas that escapes through the low-conductance section. Because the quantity of gas escaping is small and the gas capture efficiency of the turbo system is high, there is a time lag of several minutes between reducing the gas input and the pressure stabilizing. A 20 l/s ion pump minimizes this time by pumping away gas from the volume at the exits of the canal.

After the beam traverses the stripper canal it enters another low-conductance section before passing through the region housing the foil stripper. Thus gas can be used to dissociate molecules before foil stripping or the gas can be removed and the foil stripper used on its own.

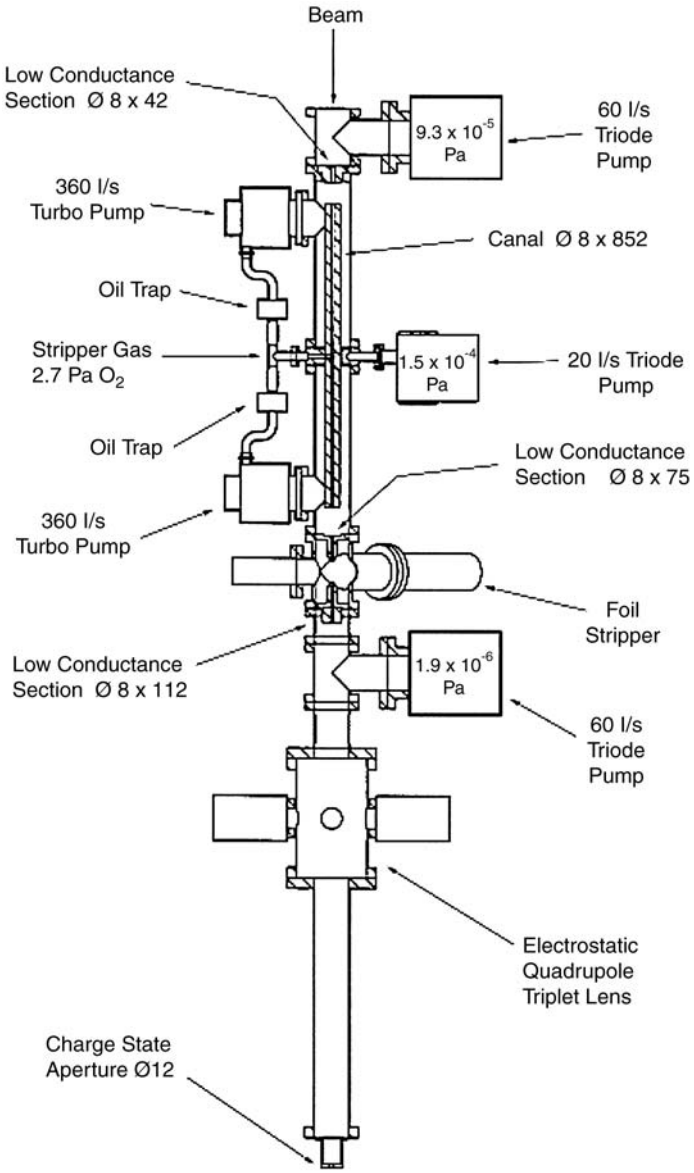

Fig. 10.3. Terminal stripper system in the ANU 14UD Pelletron. The diameters and lengths of the low-conductance sections and of the stripper canal are shown as "$\emptyset \times$ length" in mm

10.5 Foil Stripping

Gas stripping is perfectly adequate for the ions lighter than carbon used in the early life of tandems. As tandems started to exploit ions heavier than lithium, the need for higher energy meant that the higher charge states available from carbon foil strippers were required. This necessitated lenses to focus the beam scattered from them, as well as associated optics to stop the beam striking the high-energy tube. Electronics-free versions of foil strippers were also spark-immune, but foil thickening and breakage limited their use to ions lighter than about sulfur (Box 6).

The higher charge states from foil compared with gas stripping, a gain of two charge states for nickel beams at 15 MeV [1], comes with three costs. Firstly, the multiple scattering from the foil increases the beam emittance and thus decreases transmission. Secondly, the foil thickens under bombardment with heavy beams, resulting in a time-varying reduction in beam intensity and an increase in beam loading. Thirdly, foil lifetimes decrease as the beam mass and intensity increase. The lifetime problem has been ameliorated by the development of long-lived foils produced by various techniques (Box 6). However effective these innovations are, foil lifetime is ultimately limited by the sputtering away of the foil material [14].

Carbon stripper foils are almost exclusively used in tandem accelerators with terminal voltages up to 20 MV and for beam masses less than ~ 60 amu. Foils are successfully used for heavier-mass beams but of very low intensity for applications such as elastic recoil depth analysis using gold beams, and accelerator mass spectrometry of transuranic elements.

10.5.1 How Carbon Foils Fail

Foils almost invariably fail by splitting – well before the sputtering limit is reached. As a carbon foil is bombarded, it tightens on its frame, with stress creases radiating from the beam spot, which itself appears to remain flat, as shown in Fig. 10.4. Failure occurs as a tear, often at the edge of the beam spot or where the foil meets the frame. Once the foil is torn, the stress is relieved and if the remnant foil remains in the beam, the foil will continue to function for a very long time. This is an unpredictable but welcome event.

A confusing factor in understanding the failure of carbon foils is historic experience with carbon buildup on any foil bombarded by an ion beam in vacuum systems that contained hydrocarbons. In such vacuum systems, the buildup is generally accepted to be due to the cracking of the hydrocarbons by the beam in the beam spot. As the vacuum systems in accelerators improved, reducing the hydrocarbons in the residual gas, it was expected that foils would not get thicker and that they might last longer. This expectation proved overly optimistic. It appears that carbon migration in the foil itself continues to feed material into the beam spot, thus thickening it [14].

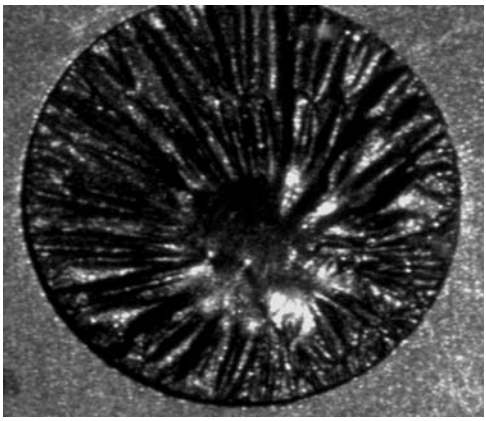

Fig. 10.4. Carbon foil stressed by beam

10.6 Second Strippers

Even higher energies are obtained for medium-mass ions by further stripping the beam a second time using a carbon foil, after the beam has gained energy from being accelerated through ∼1/3 of the high-energy tube. The increase in energy and the effects of using this second stripper on beam loading are discussed next.

10.6.1 Energy Gain and Intensity Loss

Take the case of a 15 MV tandem accelerating a nickel beam with the second stripper 1/3 of the way down the high-energy tube. After the terminal foil stripper, ∼ 27% of the beam, which is in the charge state 11^+, gains 55 MeV in traveling to the second stripper. This is a sufficiently high energy for ∼ 23% of the beam to be further stripped to a charge state of 18^+. The 18^+ component then gains an additional 180 MeV in returning to ground, resulting in a total energy of (15 + 55 + 180), i.e. 250 MeV, with an overall efficiency of ∼ 6%. This provides enough beam intensity for most nuclear-physics experiments.

10.6.2 Beam Loading

The energy benefit of the second stripper comes with other costs in addition to the intensity penalty due to charge state fractionation. There are problems caused by both multiple scattering spreading the beam at the second stripper foil, and electrons that are emitted from it. The saving graces derive from the higher beam velocity at the second-stripper, which results in proportionally less multiple scattering than for the terminal stripper and less radiation damage. This results in second-stripper foils lasting much longer than the terminal stripper foils.

The electrons can be an immediate problem if not confined to the stripper assembly. Electrons leaving the foil that experience the electric field of the accelerating tube are accelerated toward the positive high-voltage terminal. Along the way, they strike tube electrodes and so generate copious X-ray fluxes. The X-rays ionize the insulating gas, creating severe loading of the machine and dropping its voltage by many MV. Therefore the design of the second stripper must include extremely effective electron suppression. In addition to a magnetic field and an aperture near the foil, it is essential that a suppressor electrode, held at a few kV negative, be placed between the foil and the tube going towards the terminal. This combination effectively deals with the electrons.

Although most of the electrons can be suppressed, ions cannot be. Some will strike tube electrodes in the neighborhood of the second stripper, producing electrons and their concomitant X-rays, which in turn cause loading. This connects the second-stripper region to ground in parallel with the normal resistor paths, and so reduces the voltage at the second stripper. Since the final energy of the beam depends critically on this voltage, the terminal voltage must be increased to compensate. For useful nickel beams of ∼2 particle nA on target from the ANU 14UD, the terminal voltage will need to be increased from 15 MV without loading to 15.3 MV to compensate for the loading in the high-energy tube. This increases the gradient in the section between the terminal and the second stripper by 12%, requiring the machine to be conditioned, without beam, to at least 12% above 15 MV, viz. 16.8 MV. The loading worsens as both the terminal foil and the second-stripper foil thicken, scattering more beam onto the tube electrodes and so pushing the gradient beyond the value to which the machine has been conditioned. Beam loading limits the usable beam intensity in second-stripper operation.

It is challenging to operate a tandem accelerator near its voltage limit with double stripping. The loading causes the terminal voltage to rise, usually over several hours as the foils thicken. A rise of 0.3 MV with loading corresponds to the unloaded terminal voltage for another charge state combination at the same magnetic rigidity in the energy-analyzing magnet. Thus when either stripper foil breaks, and often it is not clear which foil has failed, the insertion of a new thin foil may allow the machine to lock onto the wrong beam at the higher terminal voltage. Worse still, the reduced loading suddenly frees the machine to rapidly increase in voltage, often until it sparks.

Despite the difficulties in using double stripping, it provides a valuable range of energies and intensities for a wide variety of nuclear-physics experiments. This is an especially important avenue to higher energies for facilities without postaccelerators but continues to fill an important niche even for facilities with them.

10.7 Charge State Selection

At tandem energies, the ions from the stripper are distributed over a range of charge states; see Box 5. The maximum intensity in any single charge state is $\sim 10\%$ for heavy beams and up to 50% for light beams [1]. Often experimenters who want the maximum possible energy choose a higher charge state and so will accept a sacrifice in intensity. A significant fraction of the other charge state beams, usually of higher intensity than the chosen one, may strike electrodes in the high-energy tube, compromising the voltage-holding ability of the machine. The several charge states from the terminal stripper can cause a confusion of beams exiting the machine when it is operated with double stripping. A charge state selector eliminates this confusion of beams by insuring only one charge state beam reaches the second stripper.

However, experience has shown that the confusion from adjacent charge states transmitted along with the desired one is not as serious as feared. Thus the complete elimination of adjacent charge states is not essential to the operation of heavy-ion tandems employing second strippers. This is just as well, since in a machine designed without a charge state selector in mind, there is usually insufficient space in the terminal to install one. Newer machines with more generous terminal space are able to employ various types of charge state selectors [10].

10.7.1 Suppression of Undesired Charge States

The selector steers the various charge state beams with an angular displacement proportional to the charge. The displacing field is adjusted so that the desired charge state beam goes though an aperture, which stops the ones that shouldn't be transmitted. The desired beam has first to be returned to the axis and then redirected along it. In a compact terminal, there is usually not enough space to accomplish this in order to uniquely select one charge state, and so some intensity of adjacent charge states gets through the selection aperture and is presented to the high-energy tube. The unwanted beam may be transmitted without striking the tube electrodes or be stopped in dead sections between the accelerator tubes [10]. In either case, the beam loading is adequately reduced.

A simpler solution to enhancing the transmission of the desired charge state from the terminal combined with the suppression of undesired ones is to focus the various charge state beams through an aperture at the entrance to the high-energy tube. This solution does require adequate space in the terminal between the lens and the charge state aperture for the lens substantially to converge the beams through it, as shown at the bottom of Fig. 10.3 [5]. The beams with substantially different charge states will be spread out across the aperture, with only on-axis beams getting through. These will be transmitted without striking the tube. The beams with adjacent charge states require about the same lens strength and so also will be transmitted without

striking the tube. This lens also serves to collect multiply scattered beam for transmission through the high-energy tube. The more elaborate charge state selectors include a lens for this purpose mounted directly at the entrance to the high-energy tube.

10.8 External Stripping

The desire for heavy-ion beams of higher energy than can be produced by tandems motivated the development of postaccelerators injected by tandems. Since the energy gain of the postaccelerator is proportional to the charge state of the injected ion, stripping of the beam after tandem acceleration is attractive.

The energy gained by an ion in a postaccelerator also depends upon how well the ion velocity is matched to the velocity acceptance of the post accelerator. A linac whose entrance section is optimized for an ion velocity of 0.1 times the speed of light, i.e. $\beta = 0.1$, is best matched to a 275 MeV nickel beam but can cope with energies down to 175 MeV. In a 15 MV tandem, the 275 MeV beam requires double stripping, with the concomitant reduction in beam intensity, while for the 175 MeV option, single terminal stripping to 12^+ suffices. External stripping to charge state 25^+ will compensate for the lower injection energy, provide similar beam intensity and avoid the difficulties of double foil stripping.

The lifetime of an external stripper foil is extremely long, since the beam intensity is small and the radiation damage from the high-energy beam is also small.

A tandem injector optimized for stable and reliable heavy-ion beams would use gas terminal stripping plus external foil stripping. The matching postaccelerator would have resonators capable of accepting the resulting lower-β beam.

References

1. J.L. Yntema: Nucl. Instr. Meth. **122**, 45 (1974)
2. R. Middleton: Nucl. Instr. Meth. **214**, 139 (1983)
3. E.P. Kanter, P.J. Conney, D.S. Gemmell, K.-O. Groeneveld, W.J. Pietch, A.J. Ratkowski, Z. Vager, B.J. Zanbransky: Phys. Rev. A **20**, 834 (1979)
4. P. Thieberger: Nucl. Instr. Meth. **220**, 45 (1984)
5. D.C. Weisser: Rev. de Phys. Appl. **12**, 1306 (1977)
6. C.M. Jones: In: *Proc. 3rd Int. Conf. on Electrostatic Accelerator Technology*, (IEEE report 81CH163-4, 1981), ORNL, Oak Ridge, Tennesse, p. 23
7. G.L. Weissler and R.W. Carlson, *Vacuum Physics and Techniques*, New York Academic Press, 1979, p. 16
8. K.H. Purser: In: *Proceedings of the First International Conference on the Technology of Electrostatic Accelerators*, Daresbury (DNPL/NSF/R5, 1973) p. 39

9. J.B. Schroeder, C.W. Howell, G.A. Norton: Nucl. Instr. Meth. B **24**, 763 (1987)
10. H.R.McK. Hyder, J. Ashenfelter, J. Baris, C.K. Bockelman, R.O. Hamburger: Nucl. Instr. Meth. A **328**, 126 (1993)
11. D. Weisser, D. Anderson, A. Cooper, K. Fifield, G. Foote, A. Harding, N. Lobanov, A. Muirhead, H. Wallace: In: *Proc. 31st Symposium of Northeastern Accelerator Personnel*, ed. by F. Dworschak, R. Holzele (1997), Forschungscentrum, Jüllich, Germany, pp. 19–30
12. R. Hellborg, K. Håkansson, M. Faarinen, M. Kiisk, P. Persson, G. Skog, K. Stenström: Pramana – J. Phys. **59**:5, 725 (2002)
13. G. Bonani, P. Eberhardt, H.J. Hofmann, T.R. Niklaus, M. Suter, H.A. Synal, W. Wölfli: Nucl. Instr. Meth. B **52**, 338 (1990)
14. R.L. Auble, J.K. Blair, D.M. Galbraith, C.M. Jones, P.H. Stelson, D.C. Weisser: Nucl. Instr. Meth. **177**, 289 (1980)