PRAMANA
— journal of
physics

Vol. 59, No. 5
November 2002
pp. 725–737

Mechanical design of the recirculating, terminal pumping in the Lund Pelletron, and experimental experience

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Abstract. A recirculating terminal pumping system has been installed in the 3 MV Pelletron tandem accelerator in Lund. An extremly limited space in the high voltage terminal and the absence of electrical power in the terminal, forced us to provide a unique design for the installation and powering of the new pumps. Details of the technical design, as well as experience of the use of the new system for accelerator mass spectrometry, will be given.

Keywords. Terminal pumping system; AMS; Pelletron; electrostatic accelerator; accelerator mass spectrometry.

PACS No. 29.17

1. Introduction

Among the different types of applications of electrostatic accelerators, accelerator mass spectrometry (AMS) may be the technique with the most extreme technical requirements on the accelerator system itself. This is true for most of the individual parts of the system. For example, for the ion source – in which the sample of partly unknown composition is ionized – a high and stable production efficiency of negative ions as well as a low memory effect are essential. For the injector and the low-energy side – from which the ion beam from the source is to be transmitted to the accelerator – good mass and energy resolution are important. Another important character of the injector and low-energy side is the possibility to transfer the beam with a minimal increase in the emittance and to fit the emittance to the accelerator acceptance. For the electrostatic tandem accelerator itself a stable terminal high voltage, a high beam transmission as well as an efficient and long-lived stripper medium are important. For the high-energy analyzing system a high mass- and energy-resolution should be obtained by a combination of analyzing units (such as dipole magnets, velocity filters, electrostatic analyzers) with different requirements on the beam. New, dedicated AMS systems are designed on the basis of these and similar criteria. For tandems that were originally designed for a nuclear physics programme and later on taken over for AMS, which is still the case at many AMS laboratories, these requirements were not of primary concern at the initial installation. The 3 MV Lund Pelletron tandem accelerator was designed at the beginning of the 1970's. The ion beams used in Lund during the first few years were protons, deuterons and, to a small extent, helium ions. In connection

with the introduction during the second part of the 80's, of the AMS programme in Lund [1] a new ion source was built [2], better low-energy optics were designed [3] and several new optical units were installed on the experimental line [4]. A new, high-resolution injector has just recently been installed and is now under final testing [5].

One of the requirements of the accelerator mentioned above, namely 'an efficient and long-lived stripper medium', can be better met with a gas stripper than with a foil stripper. During irradiation, the thickness of the foils changes in the irradiated area, and eventually the foils disintegrate. This change in thickness leads to a variation in the energy loss and in the scattering of the ions passing through the foils, and therefore to a change with time of the transmission through the accelerator system. This will in turn influence the quality of the AMS results. Gas strippers have a better homogeneity compared to foils and their pressure can be kept constant with time, i.e. a constant stripper medium 'thickness' with time will be obtained. The Lund Pelletron, as well as many other old tandems around the world, was designed to have the stripper gas leaking out of the stripper cell, then to be pumped through the accelerating tubes using pumps outside the accelerator tank. This leads to a considerably increased pressure in the tubes. This will degrade the tube performance and lower the transmission by spreading the beam by collisions and by charge-exchange processes with residual molecules. This is most significant in the low-energy accelerating tube since poor vacuum significantly decreases the transmission due to charge exchange from X^- to X^0 [6]. Maximum transmission through an accelerator, in which the stripper gas is pumped through the accelerating tubes, is reached at a stripper-gas pressure below that required to obtain the equilibrium charge-state distribution. In order to improve the transmission using a gas stripper, the accelerator should be equipped with terminal pumping to allow the use of a higher gas density in the stripper and to minimize any effect on the vacuum in the accelerating tubes outside the gas cell.

Our work for a new stripper design including recirculating terminal pumping began as a study for transmission calculations [6], and measurements of the pressure profile in the accelerator tubes [7] related to our AMS project. Results of these calculations and measurements clearly showed the limitation of our original stripper design without terminal pumping. In this paper we report a new gas stripper, including terminal pumping, which has been designed, installed and used for our AMS programme for a few years. The design of the new system and a test of its mechanical features, as well as an investigation of the quality of the stripper system for AMS experiments are reported. Two preliminary reports about the mechanical design of the terminal pumping system can be found elsewhere [8,9].

2. Design of the system

2.1 *The stripper housing and the terminal pumping*

Our new installation is based on our existing stripper housing. This housing – the original NEC stripper housing delivered with the accelerator – was slightly rebuilt some years ago to include a double valve equipment [10], to be used during foil replacement. The advantage of using the existing stripper housing is obvious in the event of a failure of the terminal pumps. The accelerator can then be used for foil stripping with optical conditions very similar to those before the rebuilding. Both foil (provision for 100 foils) and gas stripping are available. The stripper canal has a total length of 400 mm, with an excess for the

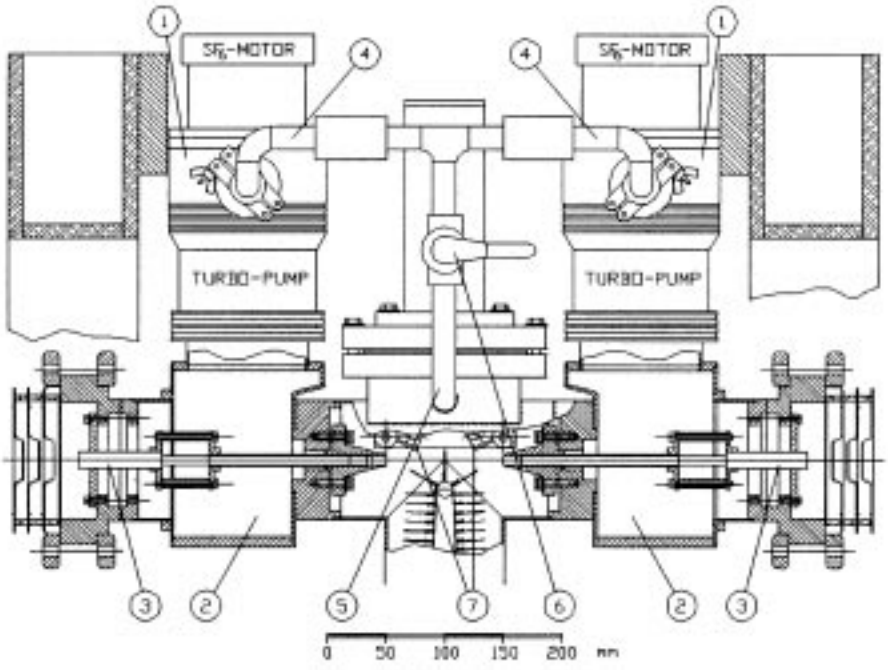

Figure 1. Schematic drawing of the stripper system. 1 – turbomolecular pumps, 2 – high conductance housing, 3 – limiting conductance pipes, 4 – pump outlet pipes, 5 – stripper housing gas inlet, 6 – valve, 7 – double valve.

foil mechanism of 100 mm. The inside diameter of the canal is 8 mm. In the new design the stripper gas leaking out of the stripper canal is re-circulated by two turbo-molecular pumps (position (1) in figure 1) back to the stripper housing. The pumps are a modification of Alcatel, model 5030CP. The idea of using re-circulating pumps in the terminal was reported for the first time at the beginning of the 80's [11] and has since then been used in several new installations as well as in old, rebuilt systems, e.g. ref. [12]. The pumps are connected to the housings (2) of high conductance on each side of the stripper housing. The beam enters the first pumping housing through a limiting conductance (3) (diameter 10.5 mm and length 70 mm, corresponding to a conductivity of 2.0 l/s) and leaves the second pumping housing through a similar conductance (3). These short and limiting pipes (3) do not influence the beam acceptance. However, they reduce the gas flow out of the stripper housings into the accelerating tubes considerably. The outlets of the pumps (4) are connected to the gas inlet (5) of the stripper housing. The inner diameter of these outlet lines is 16 mm. In this line a valve (6) is placed. This valve, together with the double valve equipment (7) mentioned above, gives the possibility to isolate the stripper housing from the rest of the system, e.g. when foils are to be replaced, leak testing is undertaken etc.

On the basis of geometrical considerations, between 90 and 95% of the gas is assumed to be re-circulated. New gas to replace the gas that is pumped away along the accelerating tubes is led in from a reservoir of about 2 l, through a hand-operated service valve and

Figure 2. A photo of the terminal with the terminal enclosure withdrawn in the direction of the high-energy column. In the background the tank at the high-energy end is seen.

a needle valve operated from earth via a rod. The time constant of the system is rather short, about 2–4 min. The pressure in the terminal cannot be directly measured while the accelerator is in operation. However, it has been measured during maintenance and is therefore known to be 5×10^{-3} Pa during foil stripping and in the 10^{-1} Pa and 10^{0} Pa ranges during gas stripping without and with terminal pumping, respectively. In figure 2, a photo of the terminal is shown.

2.2 *The powering of the terminal pumps*

The space in the terminal became very limited some years ago after a second charging chain system and the double valve equipment were installed. This, together with the absence of electrical power in the terminal, required a new and unusual design for the powering of the terminal pumps. The original electrical motors – mounted inside the vacuum – have been replaced by motors driven by compressed SF_6. These new motors have, of course, been placed outside the vacuum and the connection between the pumps and the motors is magnetic. In the first version ordinary, commercially available air-motors (Atlas Copco, model PIV-5020ACE50) were used. The lifetime of these motors was, however, very limited even though they were designed for continuous use. In the second version, motors constructed at our laboratory were built from a one-stage turbine wheel.

The compressed SF_6 for the motors is obtained from compressors – one for each pump – placed in a separate tank of about 1 m^3. In figure 3 a schematic drawing of the system for powering the turbo-molecular pumps is shown. Gas is transferred from the accelerator tank (containing 100% SF_6) to the compressor tank via a water cooled heat exchanger (position (B) in figure 3) and a pressure-reducing valve (C). The latter provides a pressure adjustable

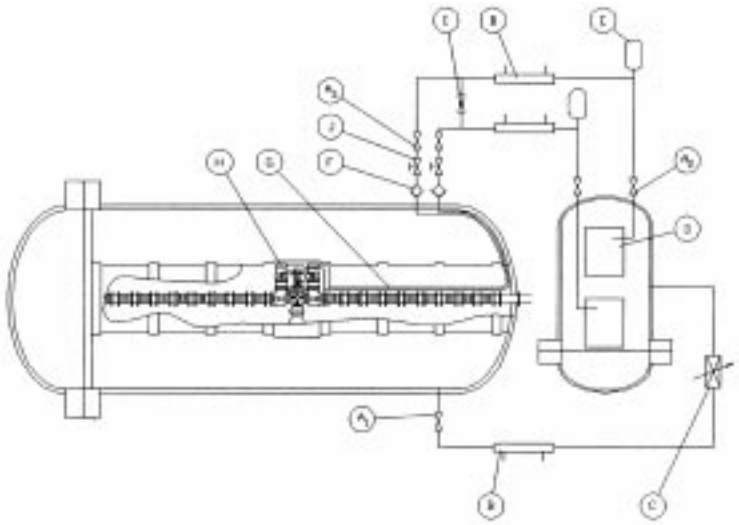

Figure 3. Schematic drawing of the compressor system. A1–A3 – valves, B – heat exchangers, C – pressure reducing valve, D – compressors, E – buffer tanks, F – check valves, G – teflon tubes, H – motors of the turbo-molecular pumps, I – shunt valve, J – needle valve.

between 0.1–0.4 MPa in the compressor tank. In this way the two compressors (D) (Atlas Copco oil-free rotating compressors, capacity 4.2 l/s at 1 MPa air, model Scroll-SF4-10) are fed with gas of a constant pressure. The outlet from the compressors (with a pressure of about 1.0 MPa) is via small buffer tanks (E) whose volume is 2 l each and water-cooled heat exchangers (B) connected to a flange in the accelerator tank close to the high-energy end. Between the flange and the terminal the compressed SF_6 is led through teflon hoses (G) and feeds the motors (H) of the turbo-molecular pumps. Originally various types of hoses for compressed air were used. However, these did not withstand the high voltage and were damaged by the sparks created. The solution finally chosen was to use teflon-(PTFE) hoses connected to metalic feed-throughs in the various sections of the column. The expanding gas leaves the motors and enters the accelerator tank.

2.3 *Design of the turbine*

In figure 4 a turbo-molecular pump and its motor are shown. The principle of the turbine – working on the reaction turbine principle – is quite simple. Compressed SF_6 gas from the compressor system mentioned above enters the centre of the turbine rotor through holes in the shaft. Through four tangentially placed holes in the outer periphery of the rotor the gas is expanded to the pressure of the accelerator tank. The resulting reaction forces acting on the rotor give the necessary torque. This construction has been found to have a high efficiency and the rotor is able to reach speeds up to the nominal speed of the pumps. In one of the first designs, a turbine of the impulse type was used. The main drawback of this construction was that not even 75% of the nominal speed could be attained. In figure 5 the design of the turbine wheel now in use is shown in detail.

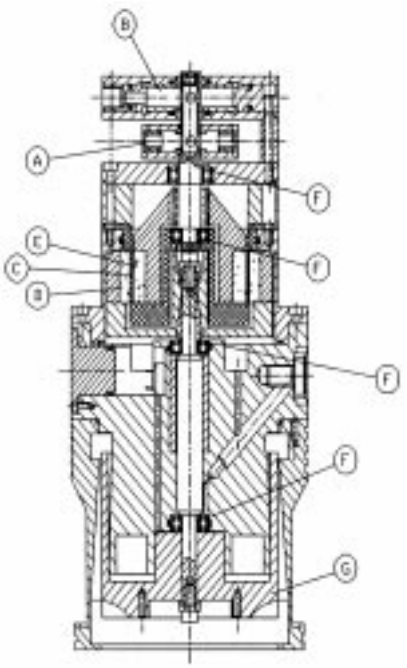

Figure 4. Schematic drawing of a turbo-molecular pump and its motor. A – turbine wheel, B – pressure chamber, C – wall between vacuum and SF_6 gas, D – magnetic ring inside vacuum, E – magnetic ring in SF_6 gas, F – ball bearing, G – turbo-molecular pump wheel.

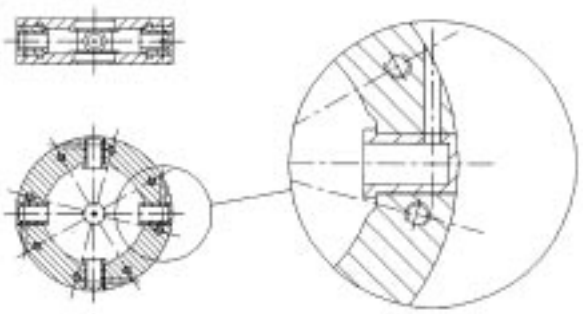

Figure 5. Schematic drawing of the turbine wheel (part A in figure 4) showing the design appropriate to the reaction mode.

2.4 *Design of the magnetic coupling*

As can be seen in figure 4, in the design of the magnetic coupling between the pump inside the vacuum and the turbine motor outside the vacuum, rods of permanent magnets (diameter 8 mm, length 24 mm) are located parallel to each other in two rings. The two magnetic rings are placed on either side of the vacuum wall. In the original design the

bigger magnetic ring was located outside the vacuum and was connected to the turbine, and the smaller magnetic ring was inside and connected to the pump-shaft. To achieve a lower gas resistance when these rings are rotating, the construction has been changed so that the smaller ring, with an outer diameter of 64 mm, is outside the vacuum and the bigger ring, with an inner diameter of 68 mm, is inside the vacuum and mounted directly on the turbo-shaft.

2.5 *Balancing the rotating parts*

The magnetic coupling parts – both inside and outside the vacuum – were balanced by a commercial company (Volvo Aero Corporation, Trollhättan, Sweden). The specified quality after the balancing is reported to be better than 1.5 g mm in both planes, measured at a rotating speed of 2745 r/min. Older versions of these rotating parts, which had not been balanced, worked only for a limited time before the ball bearings started to fail.

2.6 *Use of new types of ball bearings*

As can be seen in figure 4, four ball bearings are used in each pump. The standard bearings first used had a very limited lifetime. Despite the fact that they were designed for use at a speed of 36000 r/min (after an initial maximum limit of 20000 r/min during at least 10–20 h of use), they broke after a short time. The standard bearings have therefore been replaced by high precision, hybrid bearings (model 608-2RZTN9/HC5C3WTF-1 and 6001-2RZTN9/HC5C3WTF-1 produced by Svenska Kullager Fabriken, Göteborg, Sweden), to achieve a longer lifetime. These new bearings have now been used at a speed of up to 22000 r/min for time periods of totally 500 h each without any problem. The bearings were originally greased at the factory. Before being mounted, the bearings to be used inside the vacuum were first cleaned with trichlorethylene and thereafter lubricated with a special type of grease developed by Alcatel (delivered by Löwener-Vacuumservice AB, Baazgatan 6, SE-431 61 Mölndal, Sweden) for use in turbo-molecular pumps.

2.7 *Cooling of the compressors*

The total electric power consumption of the two compressors is 8 kW. To keep the temperature of the SF_6 gas and the compressor units at an acceptable level the main part of this power has to be cooled away. Therefore water-cooled heat exchangers (position B in figure 3) on the gas inlet and outlet of the compressor tank, as well as the coolers in front of the compressor inlets inside the tank, were installed in the original design. The coolers inside the tank – made of aluminium and designed for use in tracks – were constructed for oil as the cooling medium. We found that they could not be used with water for a prolonged period, since after some time they started to leak and the dew point of the SF_6 gas changed considerably. After replacing water with oil as the cooling medium and using a pump outside the compressor tank to circulate the oil through a water-cooled heat exchanger, these coolers have worked for a few years without any problem. One more cooler has been introduced. It consists of a copper pipe (outer diameter 12 mm and length 25 m) wound into a

helix and placed inside the compressor tank. After this latest modification the temperature of the compressor tank can be maintained below 40°C.

2.8 *Turbine speed*

The speeds of the turbines are easily adjusted by means of the reducing valve (position C in figure 3) on the inlet of the compressor tank. Table 1 shows the speeds obtained at different pressures in the compressor tank. The system has a shunt-valve (I) between the two high-pressure lines just outside the accelerator tank. Just after the shunt-valve, two needle valves (J), one on each line, are installed. By these the speeds of the two turbines can be adjusted to have a similar value if necessary. This is described in more details in §3.

2.9 *Speed gauge*

To have the possibility to check the speed of the two turbines, two gauges – one on each turbine – have been installed. Light from a lamp positioned outside the tank is sent by two optical fibres through a port in the tank and along the high-energy column up to the terminal. The light hits the turbine wheels of the two pumps and is reflected from a white spot on the wheels, is then transmitted by two optical fibres along the high-energy column to earth, through the same port in the tank, to preamplifiers just outside the tank. The information on the speed is finally displayed on two digital meters on the accelerator control console.

3. Starting procedure

To start a turbo-molecular pump and bring it up to its nominal speed, a slow increase of the speed over several minutes is normally achieved with the help of an electronic unit. As the electrical motors in our installation have been replaced by gas-driven turbines, a detailed starting procedure has been developed.

Table 1. The relation between the pressure in the compressor-tank and the speeds of the two turbo-molecular pumps. This relation is slightly changing as a function of the age of the bearings in the pumps. In these measurements the pressure in the accelerator tank was kept at 0.63 MPa.

Compressor tank (MPa)	Turbo-molecular pump #1 (r/min)	Turbo-molecular pump #2 (r/min)
0.24	14470	14670
0.26	15888	15970
0.28	17360	17630
0.30	18570	19000
0.32	19960	20060
0.34	21140	21300
0.36	22810	23100
0.38	23670	24000

When the terminal pumping is not in use the compressor tank is isolated from the accelerator tank. Moisture diffusing out of the various surfaces in the compressor tank (the tank itself, compressors, coolers etc.) and accumulating in the gas will, during the start-up of the terminal pumping, enter the teflon hoses (position G in figure 3) and temporarily give a considerable increase of moisture in the hoses. After leaving the turbines the damp gas will quickly be mixed with the dry gas in the accelerator tank. The gas in the accelerator tank is continuously recirculated through a dryer and a dew point lower than –55 °C is normally always valid [13]. This low dew point (corresponding to below 20 ppm of moisture in the gas) has earlier been reported to be important [13], as this has a deleterious effect on the high voltage performance.

In the earliest preliminary tests of our new system the accelerator was sometimes at high voltage when the turbines were started. The relatively high moisture level that appeared in the teflon hoses caused some sparks along and inside the hoses and on some occasions the teflon hoses were even punctured. Therefore the requirement always to have the accelerator high voltage switched off when starting the turbines is included in the starting procedure.

The starting procedure is to open all the valves for cooling water (not shown in figure 3), as well as the gas valves (A_2, A_3) between the compressor tank and accelerator tank. The circulation of oil for cooling the compressors is started as is one of the two compressors. The shunt-valve (I) is normally in the open position, and therefore both turbines will be fed with compressed gas and should start rotating. The shunt-valve is normally only adjusted to recognize source of a problem. The valve (A_1) between the accelerator tank and the compressor tank is still closed and therefore the pressure in the compressor tank decreases. When this pressure is 0.08 MPa (i.e., slightly below normal atmospheric pressure) the second compressor is also started. Now it is time to adjust the inlet valve (A_1) to the compressor tank and open it so that a slight noise from streaming gas can be heard. This valve should be opened in small steps over some 10–15 min so that small increases can be seen in the pressure of the compressor tank. During this procedure the turbine speeds should be checked regularly and a slow increase on both turbine speeds should be the result. The speed normally used is about 20000 r/min (which is 25% below the nominal speed for this type of pump). As can be seen in table 1 this speed is obtained at a compressor tank pressure just above 0.3 MPa for an accelerator tank pressure of 0.6 MPa. After finishing the start-up procedure of the turbines, the charging chains in the accelerator can be switched on and the terminal high voltage conditioned to the required value, the beam is taken through the accelerator and the stripper gas is adjusted for optimum stripper process. If the speeds of the two turbines are too different this can be adjusted by having the needle valve (J) to the turbine with the lower speed completely open and the other needle valve adjusted to reduce the speed of the turbine with the higher speed.

When shutting down the operation of the turbines the steps described above are in principle done in the reverse order. Valve A_1 between accelerator tank and compressor tank is closed. After the pressure in the compressor tank has reached 0.1 MPa both compressors are switched off and valves A_2 and A_3 are closed. After some minutes the oil cooling pump and the cooling water can be closed.

4. Test of the system

For our AMS experiments the terminal pumping has proved to be a major improvement to our accelerator system. Use of the terminal pumps increases the beam transmission

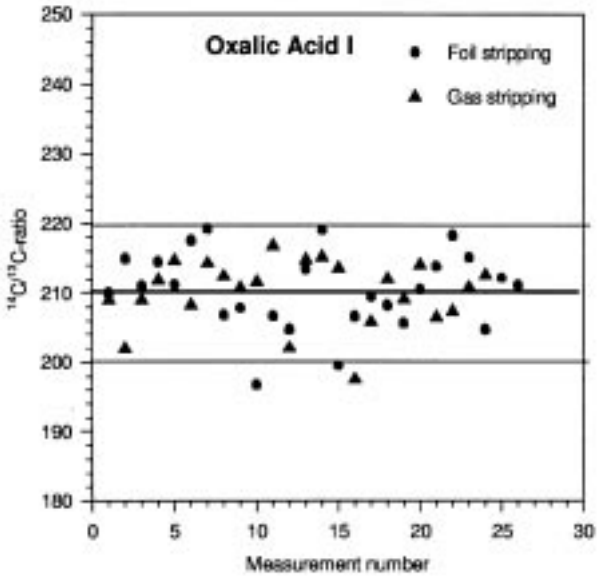

Figure 6. $^{14}C/^{13}C$-ratio for the oxalic acid I standard using foil- and gas-stripping, respectively. The mean value as well as the ± 2 sigma limits, calculated from counting statistics, are indicated.

through the accelerator and has made the gas stripper available for ions which previously could not be used with this stripper system. It is especially important for our heavy ion AMS projects, such as the ^{26}Al [14] and ^{59}Ni [15] projects, but it is also useful for the ^{14}C [16] project, as a much more stable stripper medium is obtained.

The improvement in the quality of the AMS is illustrated in figure 6 by the spreading of the $^{14}C/^{13}C$-ratio measured in a series of tests of the oxalic acid standard, Ox I. The ratio of the statistical spread to the expected Poisson distribution from 26 independent measurements was about 1.26 using foil stripping. Using the new gas stripper this ratio, determined from 24 independent measurements, was reduced to close to 1.0, i.e., only the statistical uncertainty will influence the quality of the results. The measurements were made during two experimental periods each lasting 72 h. The runs were taken in November (foils) and December (gas stripper) of 2001.

In a preliminary test of the terminal pumping, N_2 was used as a stripper gas to strip ^{12}C and ^{13}C ions and to measure the charge state distribution in the energy interval 1.5–2.8 MeV [17]. The measurements were performed at a gas density at which the charge state distribution had not yet reached the maximum average (equilibrium) charge distribution at a given ion speed, and at a gas density, high enough to reach the maximum average charge distribution. The improvement noted first is that when using terminal pumping it is possible to use equilibrium gas density. As was mentioned in the introduction this equilibrium condition can never be obtained with acceptable beam transmission and divergence without terminal pumping.

In figure 7 the charge state distributions of ^{13}C with and without the terminal pump in use are shown. Both distributions were obtained at a terminal potential of 2.4 MV and a stripper gas density of approximately 0.3 μg/cm^2. During AMS measurements when

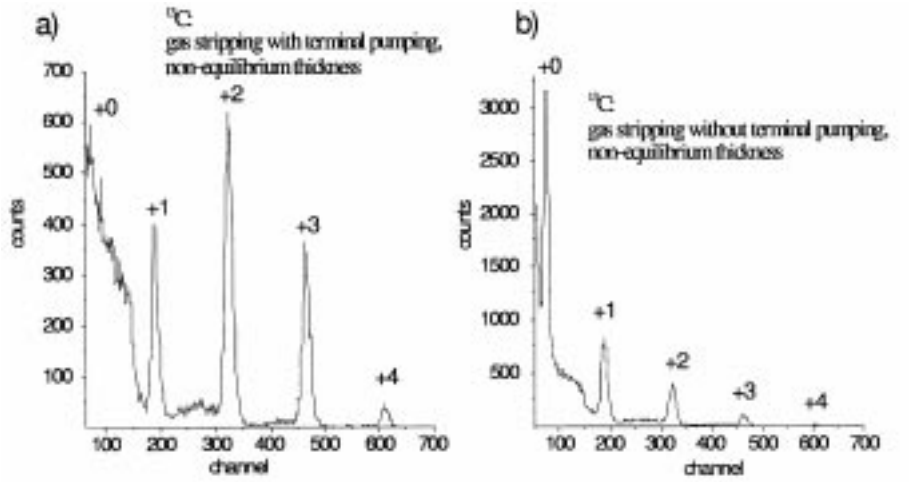

Figure 7. Rutherford backscattering spectra for the charge state distribution of a ^{13}C ion beam in a N_2 gas stripper (**a**) with and (**b**) without terminal pumping. Different charge states are tagged correspondingly.

^{14}C charge state 3+ is used, this fraction is found to be 10% and 40% without and with the terminal pumping, respectively. This is a strong evidence for the improvement of the stripper system. It must be pointed out that the spectra shown in figure 7 are Rutherford backscattering spectra of the ion beam impinged on the gold target. The cross-section of this reaction is energy dependent, i.e., in order to obtain correct ratios between different charge states, the energy constant has to be normalized.

In a recently performed test Ar stripper gas was used with both C ions [18] and also other ions, such as Be and Al [19] currently used in AMS experiments at the Lund Pelletron. The first results for ^{13}C ions show an even greater improvement with Ar as stripper gas than with N_2 gas, as can be seen in figure 8.

5. Summary

The system has been in use for a few years. The AMS investigations for the nuclear industry using ^{59}Ni ions [15] and the measurements of the cross-sections of characteristic X-ray production from projectiles and targets [20] show that the beam quality has been greatly enhanced by the installation of the new stripper system. The system has been used with a few different ion beams with excellent beam current stability and good optical quality. A 2–3 times higher ion transmission compared to the old gas stripper system and a more constant thickness of the stripper medium compared to foil stripping is attained with the new system. The advantages for our AMS measurements using the new system will be that a higher beam current can be taken through the accelerator, a higher transmission, a better quality of the beam and more stable conditions during the experiment. Measurements of the pressure profile after the installation of the new system have been made and will be presented elsewhere [21]. To increase the ion transmission, the N_2 stripper gas has recently been replaced with Ar gas.

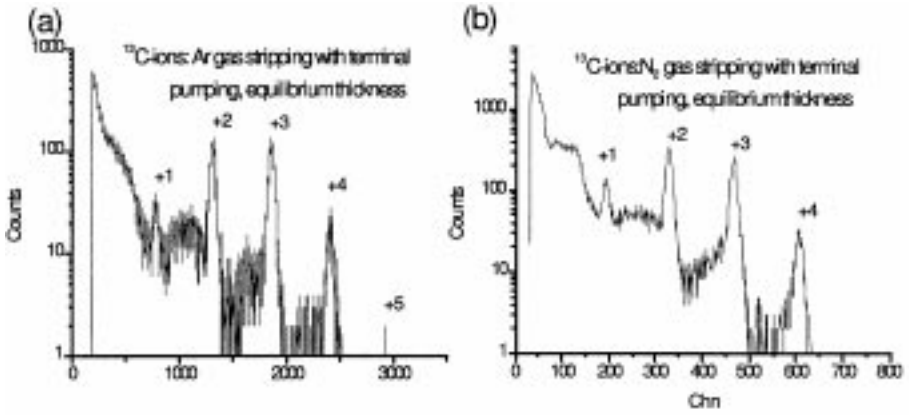

Figure 8. Pulse height distributions obtained at a terminal voltage of 2.5 MV and for two stripper gases at equilibrium thickness with terminal pumping (**a**) a ^{13}C charge state distribution in Ar, (**b**) a ^{13}C charge state distribution in N_2.

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