THE STRIPPER-SECTION OF THE UNILAC

N. Angert, K. Blasche, B. Franczak, B. Franzke
and B. Langenbeck

Gesellschaft für Schwerionenforschung m. b. H.
Darmstadt, Fed. Rep. Germany

Summary

In most heavy ion accelerators the ion beams are stripped to higher charge states after a first stage of acceleration in order to increase the efficiency of the following accelerating sections. In the UNILAC, a new heavy ion linear accelerator in Darmstadt, space was provided between the first stage Wideröe accelerator (final energy 1.4 MeV/u) and the following Alvarez accelerator for the installation of an extended stripper-section the most important elements of which are

1. the stripper, either a helically revolving drum equipped with carbon foils or alternatively a supersonic nitrogen jet,
2. a separating system of four dipole magnets by means of which one single charge state may be selected for the poststripper accelerator and another one for low energy experiments in the area aside the stripper section, and
3. two helix cavities which are used for energy and phase matching of the ion beam to the following Alvarez accelerator.

Basic principles

The efficiency of heavy ion accelerators depends strongly on the charge to mass ratio of the ion beams that are injected into the machine. Unfortunately conventional ion sources produce rather low charge states for the very heavy ions. At the Unilac U^{10+} ions are extracted from the PIG source for injection into the linac. According to the charge to mass ratio of o.o42 acceleration of uranium ions to a given velocity requires multiplication of the accelerating potential by a factor 25 and consequently of the rf power by a factor 625 compared to the parameters of an equivalent proton machine.

Therefore in most heavy ion accelerators ion beams are stripped to higher charge states after a first stage of acceleration in order to increase the efficiency of the following sections. For stripping, ion beams are passed through a thin layer of matter, either gas or solid, with a thickness between 1o and 1oo $\mu g/cm^2$. After passage through a sufficiently thick target different charge states are observed with an intensity distribution approximately similar to a gaussian function centered around the mean equilibrium charge. The mean ionisation $\bar{q}$ depends on the velocity v_i and on the atomic number Z_i of the ions. Measurements with heavy ions at particle energies up to about 2oo MeV fit a simple empirical relation [1].

$$\bar{q} = Z_i \cdot \left[1 - C \cdot \exp\left(Z_i^{-\gamma} \cdot v_i/v_o\right) \right] \qquad (1)$$

which is valid for $Z_i > 7$, $q/Z_i < o{,}7$ and $v_i > v_o = 2.19 \cdot 1o^{6}$ m/s. The parameters C and γ are adjusted to different target materials with $1 < C < 1.1$ and $\gamma = o.55$ for foil stripping and $\gamma = o.65$ for gas stripping. The mean ionisation $\bar{q}$ is much higher for stripping in foil targets than for gas stripping especially for low particle velocities where the values for $\bar{q}$ may differ by a factor 2 (see Fig. 1).

Experimental data for stripping in foils as well as in gas targets fit the following relation for the width of the equilibrium charge distribution [2,3].

$$d_{FWHM} = o.63 \cdot Z_i^{1/2} \qquad (2)$$

which is valid for $o.1 < \bar{q}/Z_i < o.7$. The maximum of the equilibrium distribution F_{MAX} follows approximately

$$F_{MAX} = 1.48 \cdot Z_i^{-1/2}$$

Thus the fraction of all ions that are available in the most abundant charge state decreases from 48 % for neon ions to 15 % for uranium ions (see Fig. 1).

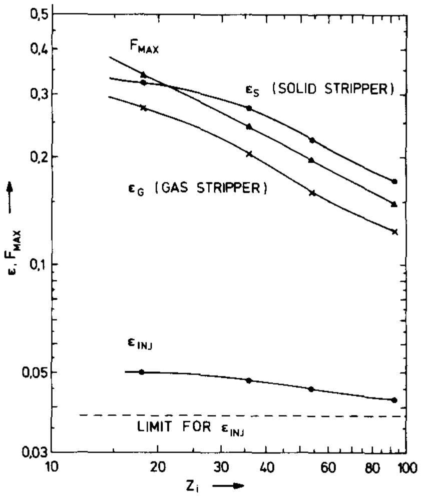


Fig. 1: Charge to mass ratio ε as function of the atomic number Z_i for ions injected into the Unilac (ε_{inj}) and after stripping, at 1.4 MeV/u, in a gaseous (ε_G) and a solid (ε_S) medium. In addition, the relative intensity F_{MAX} of ions in the most abundant charge state after stripping is shown.

As an example, charge distributions for uranium ions at 1.4 MeV/u as measured at the Unilac are shown in Fig. 2. The mean equilibrium charge is close to 28+ for stripping in the nitrogen gas jet and 41+ for carbon foils. These measured $\bar{q}$ values differ from extrapolated values according to equation (1): $\bar{q}$ (gas) = 25+ and $\bar{q}$ (foil) = 44+. In addition the width of the equilibrium distribution for gas d_{FWHM} = 7.5 is greater than 6.0 according to formula (2). There are several possible explanations for these result: influence of the electronic shell structure for different values of the ionisation q, increase of $\bar{q}$ due to the high density in the gas jet compared to dilute gas targets and finally insufficient thickness of the gas target (10 μg/cm^2) which does not completely give the equilibrium distribution.

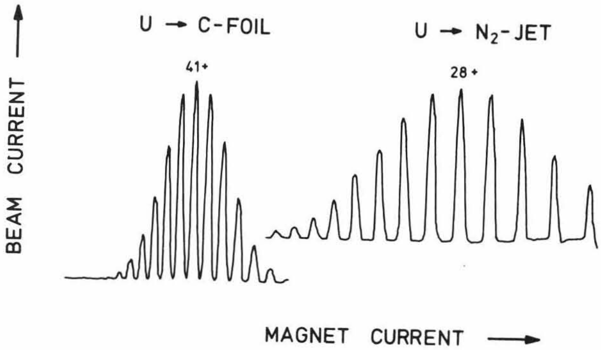
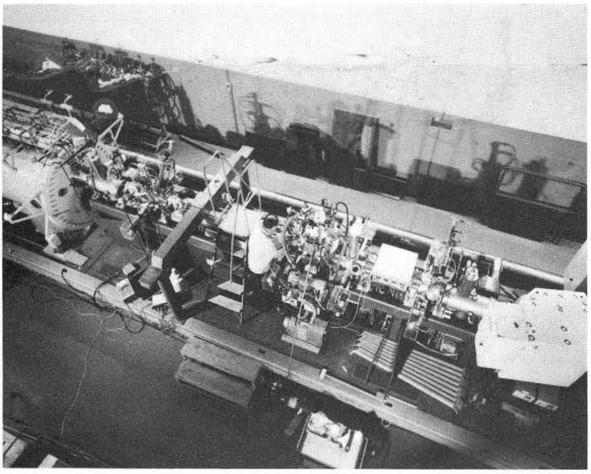


Fig. 2: Equilibrium charge distribution for uranium ions at 1.4 MeV/u after stripping in the supersonic nitrogen jet and in carbon foils.

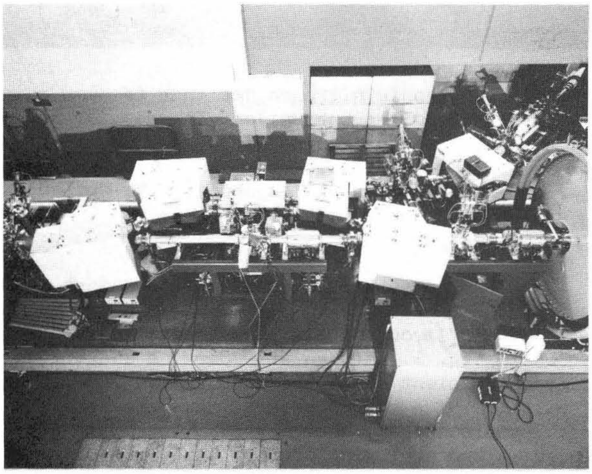
In the Unilac the optimum position for the stripper is at 1.4 MeV/u, where the total voltage for the acceleration of uranium ions to the final energy of 8.5 MeV/u reaches a minimum value of 95 MV when optimizing for gas stripping which requires a higher accelerating voltage than foil stripping. Between the first stage Wideröe accelerator and the following Alvarez accelerator sufficient space was provided for the installation of an extended stripper section (see Fig. 3). The most important elements of this section are the stripper, a non-dispersive system of four magnets for the selection of one single charge state, and two helix cavities which are used for energy and phase matching of the ion beam to the following poststripper linac.

The stripper targets

Two different stripper targets are installed: a rotating drum with a capacity of 220 foils and a supersonic gas jet for high intensity beams [4]. The stripper foils, mostly carbon foils with a thickness of about 40 μg/cm^2, yield higher charge states than the gas stripper, thus reducing the power consumption in the poststripper linac. When particle currents exceed the range of 1 μA foil strippers are destroyed in rather short time.



3a



3b

Fig. 3: The stripper section of the Unilac with the stripper and the helix cavities (a) and the charge separating system (b) which selects two singly charged beams for the poststripper and the low energy experimental area, respectively.

Therefore stripping of high current beams requires a gas target. At the Unilac a supersonic gas jet is used instead of a diluted gas target. By passing nitrogen through a Laval nozzle a gas jet with a diameter of about 10 mm is produced which crosses the ion beam (see Fig. 4). Though the jet reaches a thickness of some 10^{17} molecules/cm^2 (10 μg/cm^2) and a density that is equivalent to a pressure of 10 torr, the vacuum pressure in the adjacent beam tubes is lower than $1 \cdot 10^{-5}$ torr at a distance of 40 cm from the gas jet. Due to the speed of the gas molecules in the jet, which may reach 500 m/s, the gas flow into the beam tubes is effectively reduced. The main gas flow of more than 100 torr l $\cdot$ s^{-1} is pumped by a big roots blower (pumping speed 10^4 m ^{3}/h), which also serves as roughing pump for the linac cavities ($5 \cdot 10^{-2}$ torr).

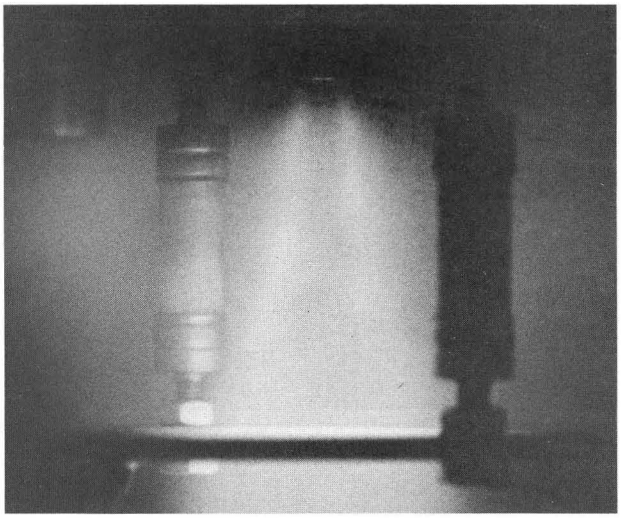


Fig. 4: Supersonic nitrogen jet that is used as gas stripper at the Unilac. The gas jet produced by passing nitrogen through a Laval nozzle was made visible by rf-exitation. The rf-electrode can be seen at the bottom.

Charge separation and beam transport

The layout of the beam transport system is shown in Fig. 5. Between stripper and poststripper linac sufficient space was provided for the installation of a charge separating system. The acceleration of all charge states which are produced in the stripping process would yield low quality ion beams with large energy spread, pulse width and emittance. Therefore this mode of operation by passing the beam with all charge states through the straight beam line is used only when high beams currents are required without need for good beam quality.

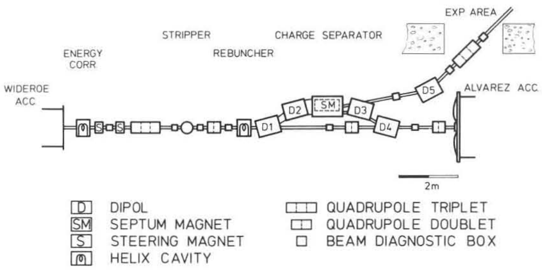


Fig. 5: Layout of the stripper section of the Unilac.

Usually one single charge state is selected for injection into the poststripper. The charge separating system consists of four dipole magnets. Between the first and the second pair of magnets the dispersion is 5.43 mm for 1 % charge difference which is sufficient for separation of one single charge state even for the highly charged uranium ions (see Fig. 6). The second pair of magnets deflects the beam back to the linac axis and compensates the dispersion of the first pair so that the complete system is non-dispersive.

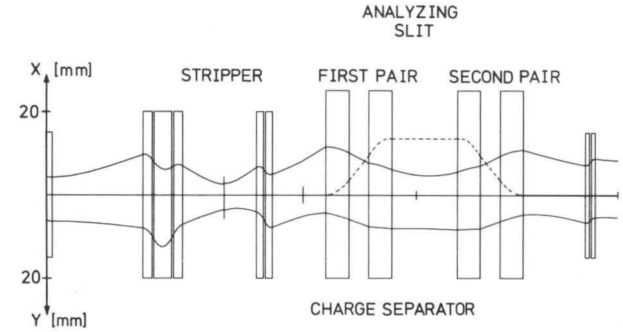


Fig. 6: Beam profiles and dispersion trajectory for $\Delta q/q$ = 2,5 % along the stripper section.

It might be noted that the charge separating system is not isodrome, the lengths of beam trajectories differing by 5.4 mm for 1 % charge difference. For example, injection of U^{40+} and U^{41+} passing the charge separator would result in a phase shift of 32^0 at 1o8 MHz for the particle bunches and therefore in reduction of beam quality.

Between prestripper linac and stripper a quadrupole triplet is installed which focuses the beam into a double waist at the position of the stripper. A small beam diameter at the stripping target reduces emittance blow up due to multiple scattering of the ions at the target atoms. That effect seemed to be more important than the reduction of life time for the stripper foils as results of increased beam current density. At both sides of the stripper the ion beam is passed through small beam tubes with a diameter of 1o mm which reduce the gas flow from the gas jet. Fig. 7 shows one of these beam tubes after several months of operation. It can be seen that bad focusing may have rather dramatic effects.

Beam matching in the longitudinal phase space

When leaving the prestripper linac the ion beam has an energy spread of about 1 %. Due to this energy spread particles drift apart along the 13 m distance of the stripper beam transport system. The resulting phase width of the particle bunches would be about $15o^0$ at 1o8 MHz at the entrance of the poststripper linac. Injection of these broad bunches would result in particle losses and in reduction of beam quality [5]. Therefore a rebuncher helix was installed for phase matching from the prestripper

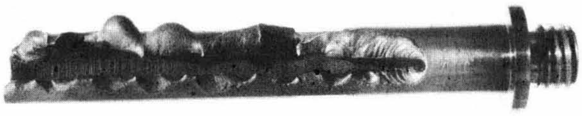


Fig.7: The 1o mm diameter beam tube just in front of the gas stripper which was damaged by a slanting high intensity beam.

into the poststripper linac.

The position of the rebuncher helix behind the stripper is nearly at the centre of the drift space. Since distances at both sides of the rebuncher have nearly equal length and since the charge state is increased in the stripper the maximum voltage in the rebuncher is only 3oo kV. Phase matching can be compared to beam matching in radial phase space. Particle bunches that leave the prestripper linac are brought to an image at the entrance of the poststripper linac. Thus the rebuncher focuses a singly charged particle beam into short bunches for injection into the poststripper linac. In the same way as focusing properties depend on the momentum of particles, the focusing properties of the rebuncher depend on the charge state of the ions. The chromatic aberration for different charge states increases the bunch width by 1o to 2o % when the beam with all charge states is passed through the straight beam line. However, different charge states are accelerated anyhow at different stable phase angles and this effect deteriorates beams quality much more than the small increase in bunch width.

In addition, matching of the beam energy is required since energy loss in the stripper target depends on the atomic number of the ions and of the target atoms, and, moreover, on the thickness of the target [6]. Due to these effects energy differences of up to 2 % are observed for different ion beams, which would deteriorate the beam quality in the poststripper linac. Therefore another helix cavity was installed at the exit of the prestripper linac which is used for compensation of the energy loss in the stripper target. The prestripper linac was designed for a final energy that is 1.5 % higher than the injection energy of the following accelerator stage. This energy difference balances in part the energy loss in the stripper, so that a total energy loss between o % and 3 % can be compensated by the energy correcting helix. Energy correction can be compared to beam deflection in the radial phase space (see Fig. 8).

During the initial period of operation only the rebuncher helix was used, which improves beam current by about 7o % and reduces the phase width of the particle bunches. The energy correcting helix will go into operation after installation of additional beam diagnostic equipment.

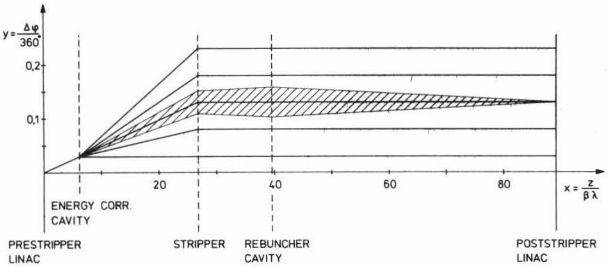


Fig. 8: Beam matching in the longitudinal phase space. Plotting phase differences versus axial position along the stripper section demonstrates that the rebuncher acts like an optical lens and the energy correcting cavity like a steering magnet. Both coordinates are normalized to $\beta\lambda$=151 mm, the slope of the trajectories reflects velocity differences.

Acknowledgement

The authors wish to acknowledge the important contributions to the design philosophy of the Unilac stripper section by Prof. Ch. Schmelzer.

References

[1] H.D. Betz, G. Hortig, E. Leischner, Ch. Schmelzer, B. Stadler and J. Weihrauch, Phys. Letters 22,643 (1966)

[2] E. Leischner, UNILAC-Bericht 1-66, Heidelberg (1966)

[3] H.D. Betz, Rev. Mod. Phys. 44,465 (1972)

[4] B. Franzke, GSI-Bericht 71-5, Darmstadt (1971)

[5] R. Friehmelt, GSI-Bericht 71-7, Darmstadt (1971)

[6] L.C. Northcliffe and R.F. Schilling, Nucl. Data A 7,3 (197o)

DISCUSSION

J. Sheehan, BNL: What is the lifetime of the foils?

Angert: Indefinite, because the current for uranium is very low.