THE UNILAC-INJECTOR

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Summary

With two dc-preaccelerators, symmetrically arranged to the axis of the Unilac, ions of all stable elements can be accelerated to 11.7 keV/u. The beam transport system bends the beam into the Wideröe linac. It works either in a nondispersive or a dispersive mode. The injector system is described and first operation experience is discussed. For several elements, up to uranium, beam parameters are given.

Introduction

According to the design aims of the Unilac, its injector system should produce and preaccelerate ions of all stable elements of the periodic table. The specific energy required for the following pre-stripper-rf-accelerator of the Wideröe type is 11.7 keV/u.[1] The lowest charge to mass ratio (q/A) acceptable by the Wideröe structure was originally fixed to $(q/A)_{min}$ = 0.046 corresponding to U^{11+}.

During the early stages of the design of the Unilac, little was known about sources for so highly charged ions. It was, however, obvious, that their lifetime was considerably shorter than for, e.g., proton sources. Therefore, considering the availability of the beam from this accelerator, one has to take into account the time necessary to change an ion source and, in case of vacuum break, for reconditioning of the accelerating column. In addition, such a change may require new emittance matching to the beam transport system. The same is valid for scheduled changes of ion species. In order to minimize this loss of beam time, a multiple source and injection system was considered. This concept led to the injector lay-out shown in Fig. 1.

There are two identical preaccelerator installations, which can be operated in parallel. Either preaccelerator consists of a 320 kV high voltage generator and two ion source terminals, one equipped with a duoplasmatron ion source for elements up to masses of about 140 and the other with

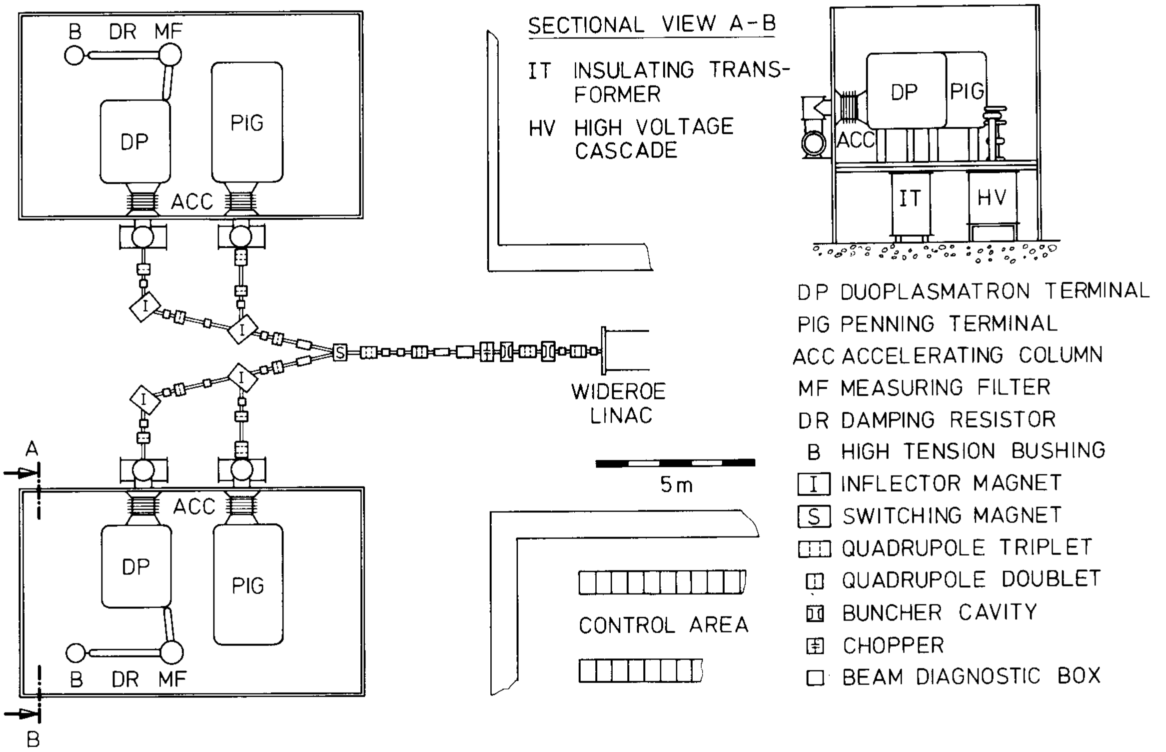

Fig. 1 The Unilac preaccelerator and low energy beam transport system.

a Penning ion source for very heavy and especially for metal ions. In the beam transport system to the Wideröe prestripper accelerator, ion beams can be separated for charge state and atomic mass number. The preaccelerator delivers beam pulses with a repetition rate of 50 Hz at a duty cycle of ⩾ 25 %. The manual control of the whole injector is done from a local control room.

Preaccelerator

Faraday-Rooms and Supplies

The preaccelerators are housed in two-storied Faraday-rooms to protect the surrounding equipment against transient waves from high voltage break downs.[2] In the basement are the high voltage generator and insulating transformers for the power transfer to the ion source platforms. On the ground floor are the ion source terminals with the accelerating columns and the high voltage bushing with damping resistor. The feed through of the power lines into the Faraday-rooms is made via wide-band rf-traps for 4 x 400 amps. Up to 50 kW electrical power can be delivered to the terminals by the insulating transformers. An oil circuit connected with a heat exchanger on ground potential provides for cooling in the terminals. Special precautions have been taken in the transformer circuits on ground and terminal potential to avoid damage due to high voltage break downs. Fig. 2 shows a schematic lay-out of the terminal supplies.

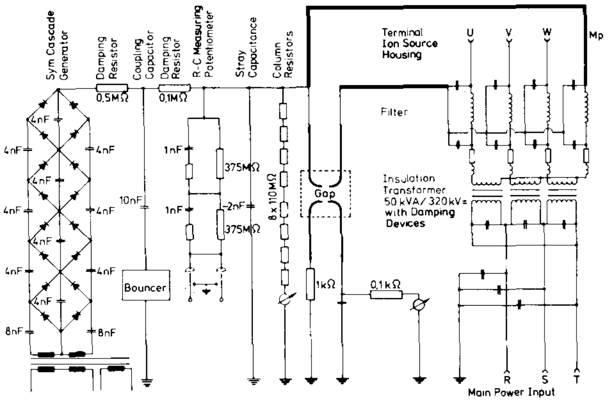

Fig. 2 Schematic of terminal supplies.

High Voltage Generator

The positive high voltage for ion acceleration is generated by a Greinacher-cascade. Maximum voltage and current ratings are 320 kV and 40 mA.

As mentioned above, the prestripper injection energy was fixed to 11.7 keV/u. Desregarding the Wideröe limitations in the charge to mass ratio, the injector can accelerate ions with $q/A > 0.0366$ to that energy. Taking into account the source extraction voltage, this installation thus allows for accelerating U^{8+} to 11.7 keV/u.

The high current of 40 mA was necessary because in the case of the duoplasmatron the total ion current must be accelerated. The voltage is stabilized by a fast bouncer system, which reduces variations due to loading and voltage ripple to 20 V_{p-p} both in cw and pulsed operation. This high voltage stabilisation is mainly required for the double drift buncher system in front of the Wideröe and, in addition, for obtaining a mass resolution of 200 in the beam transport system.

Controls and Data Transmission System

During accelerator operation the whole equipment in the Faraday-rooms is controlled from a local control section. To eliminate electrical interference the signals to and from the Faraday-rooms are transmitted through glass fiber links. Each light link transmission system consists of two transmitter-receiver units (Fig. 3). The systems are able to transmit up to 128 one bit signals with 12 ms cycling time. These systems are designed such that disturbances, e.g. by sparking in the accelerating column, neither influence time sequence or distribution of information (voter-system). The systems have parallel in- and outputs for manual and computer control. For slowly variable signals a 32-channel-analog multiplexer is used. An additional analog data link with 30 MHz band width allows observation of fast signals from the source plasmas, which are very important for diagnostic purposes.

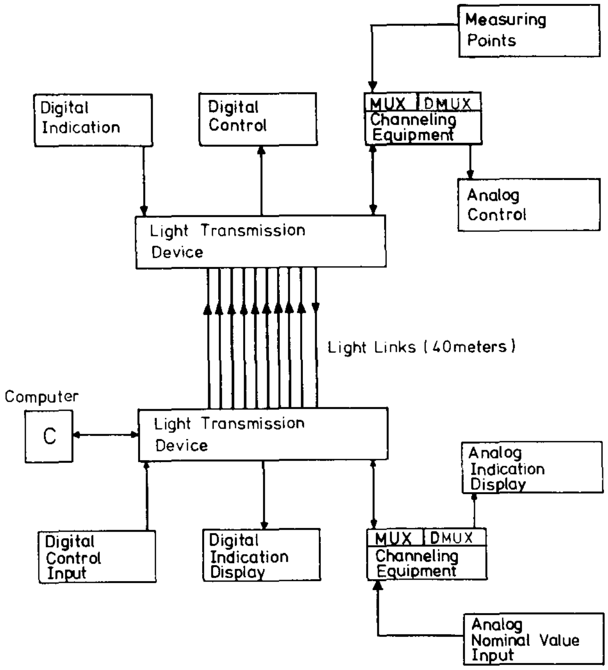

Fig. 3 Block diagram of light link data transmission and control system for high voltage generators and ion source terminals.

Ion Source Terminals and Preacceleration

High voltage can be applied either to the duoplasmatron or to the Penning terminal. The accelerating column, cantilevered on the flange of a big vacuum vessel on ground potential, is installed between the terminal and the wall of the Faraday-room. Inside the column is a single gap accelerating geometry with 5 cm gap width.

Duoplasmatron Terminal

The duoplasmatron source is directly mounted onto the accelerating column (Fig. 4). Ions are extracted with up to 50 kV negative potential out of an anodic orifice of 0.6 mm diameter. An electrostatic einzellens provides for matching the beam to the accelerating gap, in which the ions are accelerated to 11.7 keV/u. The voltages of extractor and lens are not pulsed. Separation of charge states and masses is done in the beam transport system on ground potential. Design, development and performance of the source type used has been reported elsewhere.[3]

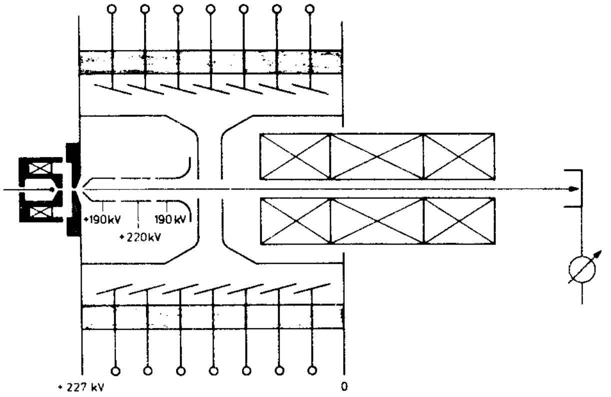

Fig. 4 Schematic of duoplasmatron source, extraction and acceleration set-up. Electrode potentials valid for $^{136}Xe^{7+}$.

Penning-Terminal

Fig. 5 shows a schematic lay-out of the beam transport within the Penning terminal. Here a source with radial extraction and heated cathode of the Dubna type is used. Our investigations on this source have been reported elsewhere.[4] The source magnet has a useful gap of 160 mm and 0.8 T maximum field. The source is at a potential of up to +30 kV, with the extractor at ground potential. Ions are extracted out of an anode slit of 10 mm x 1 mm. The ion beam with the desired charge state is deflected by 110^0 with a bending radius of 150 mm, and transported and matched to the accelerating gap by magnetic quadrupole lenses. For vertical focusing, the exit pole edge of the source magnet is rotated through an angle of 15 degrees.

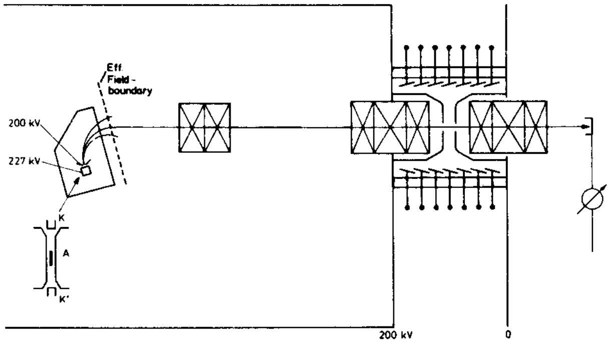

Fig. 5 Schematic of Penning source and low energy beam transport system. Denoted potentials valid for $^{136}Xe^{7+}$.

The Beam Transport System

The design and the basic parameters of the beam transport system have been chosen so that

a) 11.7 keV/u ion beams up to 1 mA and with a maximum emittance of 30 mm · mrad can be transported;

b) one single charge state can be selected;

c) the momentum dispersion allows for a mass resolution of $m/\Delta m > 200$ (dispersive mode), or

d) alternatively, the total momentum dispersion of the bending magnets is zero (nondispersive mode);

e) two ion sources can be used simultaneously in a switching mode with repetition frequencies between 1 Hz and 50 Hz;

f) sufficient space remains available for a double drift buncher, beam diagnostics and other auxiliary equipment.

These requirements led to the arrangement shown in Fig. 1. This lay-out provides convenient spacing for the installation of the ion sources; moreover each beam line includes two magnets - the 77.5^0 inflector magnet and the 12.5^0 switching-magnet - necessary for either dispersive or nondispersive operation. The small, laminated 12.5^0 magnet can be used later on as a fast switching magnet for simultaneous injection from two ion sources. The beam line between the switching magnet and the linac provides space for several quadrupole triplets that are used for beam matching to the linac acceptance in radial phase space, and for a double drift single frequency buncher.

Dispersive Mode

Most heavy ion experiments require particle beams that contain only one single isotope, whereas ion sources normally are operated with a natural isotope mixture of the different elements. Therefore in the dispersive mode the beam transport system serves as an isotope separator. The momentum resolution of a bending magnet is

$$A_p = \frac{x}{\varepsilon} \cdot \sin \frac{\varphi}{2}$$

where φ is the angle of deflection, ε the emittance, and x the beam radius in the plane of deflection at the centre of the magnet.[5] Hence, given an emittance ε = 33 mm · mrad and a radius x = 25 mm, the maximum momentum resolution A_p = 500 for the 77.5^0 inflector magnets (Fig. 6a). This value is equivalent to a mass resolution A_m = 250, which is sufficient for the separation of all isotopes.

Analyzing slits for selection of one single isotope are mounted at the position of the waist behind the inflector magnets. A second set of analyzing slits is installed behind the switching magnet, where, due to the magnification of the quadrupole lenses in between, the beam is 14 mm wide instead of 1.4 mm at the first slit.

Second order aberrations could deteriorate the mass resolution of the beam transport system. Among all possible aberrations the second order term $x|x'^2$ in the inflector magnets is predominant in practice. Achromatic imaging requires sextupole fields which were inserted between the beam waist and the quadrupole doublets at both sides of the inflector magnets.

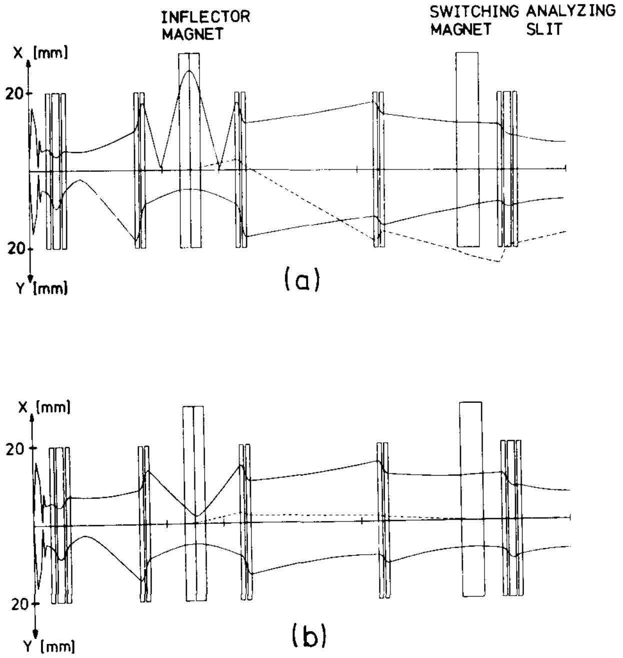

Fig. 6 Beam profiles (ε = 33 mm · mrad) and dispersion trajectory ($\Delta m/m$ = 0.5 %) for the beam line between the duoplasmatron ion source and the second analyzing slit behind the switching magnet. The system can be used either in a dispersive (a) or in a nondispersive mode (b).

Nondispersive Mode

The nondispersive mode is used when isotope separation is not necessary.

The simplest nondispersive deflection system must include two magnets. Duoplasmatron nondispersive operation can be easily achieved by means of the two doublets in the beam line between inflector magnets and the switching magnet (Fig. 6b). In the Penning line the dispersion of the ion source magnet has to be taken into account so that the quadrupole magnets before the inflector magnets are also used for adjustment of the dispersion trajectory.

The use of the nondispersive mode is restricted, however, by bunching systems (see below).

Space Charge Effects

It should be mentioned that, due to the very low particle velocity of β = 0.005, space charge effects begin to play a role already at beam currents below 1 mA. For instance, when operating in the dispersive mode, the focus at the first analyzing slit shifts downstream by 35 mm, when going from very weak intensities to a current of 1 mA. Hence, the focusing fields must be increased by about 15 % to 20 % when handling 1 mA beams.

Buncher- and Chopper-System

An electrostatic deflector, which is used to reduce the pulse repetition frequency from 50 Hz to 1 Hz when tuning the linac at very high beam currents. Later on, if time of flight experiments should require a lower repetition frequency for the particle bunches than 27.12 MHz from the linac, and, in addition, a high on-off-intensity ratio, an rf deflecting system might be used.

For matching in longitudinal phase space a double drift single frequency buncher was installed. A similar device had been successfully tested on the proton linac of the Rutherford Laboratory[6]. With this buncher we observed a trapping efficiency of up to 80 %. Although there are different types of double drift bunchers that promise even up to 90 % efficiency, the Rutherford type was preferred because it gives exceptionally compact bunches collecting about 70 % of the particles per period into a phase interval of 15^0 and an energy interval of ± 1.5 %.[7] Double drift bunchers with harmonic frequencies were ruled out because of the strong radial increase of the transit time factor. At 54 MHz and for β = 0.005, it increases by a factor of two 10 mm away from the beam axis. The double drift buncher limits, however, the pass-band of masses actually accelerated to one percent.

Technical Design

The technical lay-out of the beam transport system is shown in Fig. 7. Bending magnets and quadrupole lenses were designed for a minimum aperture of 40 mm for reasons of economy, whereas the beam tubes in between provide a diameter of 100 mm since a vacuum pressure below $1 \cdot 10^{-7}$ torr is required. The demand for this low pressure results from the fact that the total cross section for charge exchange processes σ_T can be rather large, e.g. for

Ar^{3+} ions $\sigma_T = 1.6 \cdot 10^{-15}$ cm^2/molecule at $\beta = 0.005$.[8] So at a pressure of $1 \cdot 10^{-6}$ torr one would observe charge exchange in the injection system for 9 % of Ar^{3+} ions while at $1 \cdot 10^{-7}$ torr that fraction is reduced to 1 %. Actually with ion getter pumps and turbomolecular pumps an operating pressure of $\lesssim 1 \cdot 10^{-7}$ torr is obtained.

In addition to the matching elements described so far, a number of steering magnets and several beam diagnostic instruments are installed. The latter are discussed in detail in Ref. 9.

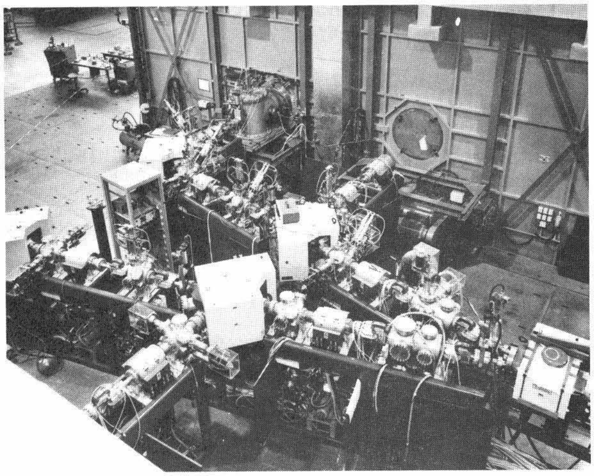

Fig. 7 The low energy beam transport system.

Injector Operation

Accelerated Ion Beams

Except for uranium, the ion sources so far are fed with natural isotope mixtures. The duoplasmatron source is used for production of rare gas ions, the Penning source for ions of both rare gases and metals. At the time being only one terminal of both types is operative. A typical isotope spectrum of a xenon-beam from the duoplasmatron source is shown in Fig. 8.Ion optics and steering are adjusted in this case to optimize for charge state 6+. The charge spectrum of an uranium beam out of the Penning sputter source is shown in Fig. 9.

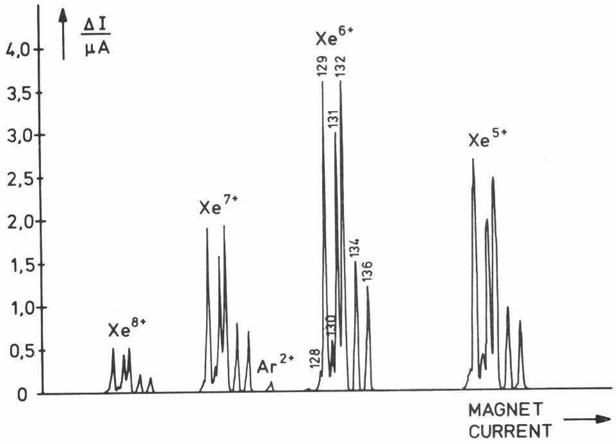

Fig. 8 Xenon charge state spectrum from duoplasmatron source. Ion optics and steering are adjusted to optimize Xe^{6+}.

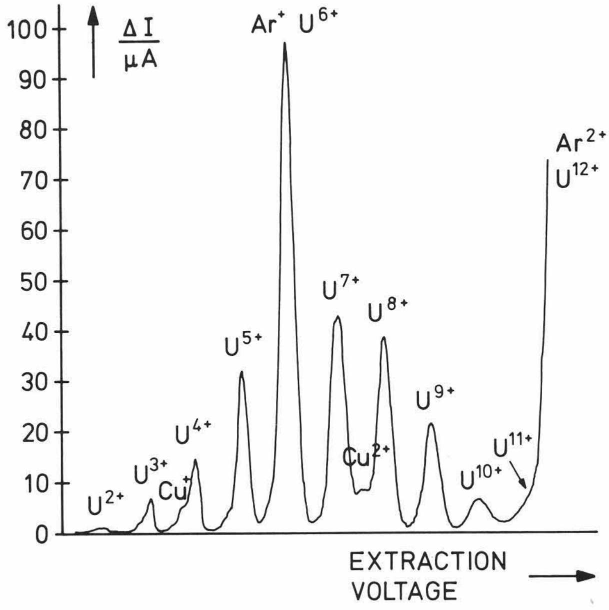

Fig. 9 Uranium charge state spectrum from Penning sputter source, obtained at constant source magnetic field by variation of the extraction voltage.

Table I shows peak intensities of ion beams so far injected into the prestripper. Up to 80 % of the peak intensities given in Table I can be focused into the phase acceptance of the Wideröe-rf-accelerator by means of the double drift buncher system.

Although designed for acceleration of U^{11+}, the system allows use of U^{9+} with the benefit of considerably increased intensity.

Beam matching to the transport system is rather easy for the duoplasmatron line. The Penning line presently causes some problems, mainly due to the lack of two power supplies for the terminal beam transport system. Therefore, an increase of the Penning intensities by a factor of two or three over those given in Table I is expected in the future.

Operating Experience

During the last 18 months the reliability of the whole installation has been considerably improved. The fraction of down time due to injector failure is now less than 20 %. In the early phase of operation we had problems with the insulating transformers. Sparks in the accelerating gap caused serious damage in two of these transformers. It was necessary to improve the mechanics in the transformers and to install additional rf-absorbers in the power cables at ground and terminal potential. Since these changes were made no further damage occured. Recently there were some break downs of light links for the terminal control. In two cases it seemed as if the resistance of the light link coatings had changed, so that they were destroyed by heating or sparks. The reason for this damage is not yet understood.

TABLE I

Isotopes accelerated with the Unilac-injector from natural isotopic mixtures. The given peak intensities have been measured at the entrance of the Wideröe.

Isotope	Charge state	peak intens. pps	ion source	duty cycle
^{40}Ar	2+	$2.5 \cdot 10^{15}$	DP	10 %
^{40}Ar	3+	$5 \cdot 10^{14}$	"	"
^{50}Ti	3+	$2 \cdot 10^{11}$	PIG	"
^{56}Fe	3+	$6 \cdot 10^{13}$	"	15 %
^{84}Kr	4+	$1 \cdot 10^{14}$	DP	20 %
^{86}Kr	4+	$3 \cdot 10^{13}$	"	"
^{84}Kr	5+	$2.5 \cdot 10^{13}$	"	"
^{86}Kr	5+	$8 \cdot 10^{12}$	"	"
^{129}Xe	6+	$2.5 \cdot 10^{13}$	"	10 %
^{132}Xe	6+	$2.5 \cdot 10^{13}$	"	"
^{136}Xe	6+	$8 \cdot 10^{12}$	"	"
* Pb	8+	$1.5 \cdot 10^{12}$	PIG	25 %
^{238}U **	9+	$4.8 \cdot 10^{12}$	"	20 %

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* isotopes not separated

** pure ^{238}U

The development of ion sources has led to lifetimes that are much longer than expected earlier on. A duoplasmatron ion source runs normally between 30 and 60 hours at 25 % duty cycle. The same is valid for Penning sources operated with rare gases. 20 hours is a typical lifetime for operation with uranium. The limiting element for both types of sources is the cathode. The down time due to source change is about two hours. But despite the fact, that source lifetimes are no more so crucial, the redundancy in the injector system still proves essential for operational reasons. It turned out, for instance, that source conditioning is necessary for stable operation, in particular for the production of high charge states. This conditioning and the matching of the source output to the beam transport system frequently consumes more time than the two hours required for the pure source exchange, pumping down and igniting of the discharge.

According to our present experience the duoplasmatron gives a more stable beam than the Penning source. In the latter case erosion in the extraction area requires a continous matching of beam optics.

In the experience of about 3000 beam hours one can state that the multiple ion source concept has proved successful. Since spring 1976 we switch between the left (DP) and the right (PIG) preaccelerator. The complete installation with four sources will be operational in 1977.

Acknowledgement

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