THE UNILAC UPGRADE PROJECT

J. Klabunde

Gesellschaft für Schwerionenforschung mbH
Postfach 11 05 52, D - 6100 Darmstadt
Federal Republic of Germany

Summary

GSI is extending its accelerator facility by a heavy ion synchrotron (SIS) and an experimental storage ring (ESR). The UNILAC has been upgraded for optimum performance in the new complex.

Two low energy injectors will be built. The first, a new linac, will consist of an ECR-ion source, a 108 MHz-RFQ and an interdigital H-type structure. It will deliver a high charge state beam at 1.4 MeV/u for further acceleration in the Alvarez section. This beam will be used for the continuation of the research program at UNILAC energies, and also for injection into the synchrotron.

The second will be a high current injector, which is expected to increase the beam intensity by up to three orders of magnitude. Low charge state ions will be accelerated by a 27 MHz-RFQ, and after stripping the beam will be injected into existing Wideröe tanks.

The poststripper section of the Unilac has been modified for time sharing operation: differing ion species, energies and intensities can be switched independently to the UNILAC experimental area or to the synchrotron on a pulse-to-pulse basis.

Introduction

In November 1986, the preparation of the site for a heavy ion synchrotron (SIS) and an experimental storage ring (SIS) started at GSI. In the meantime the SIS tunnel and the buildings have been completed, all the SIS dipole magnets and magnetic quadrupoles are in place, the first injection into the ring ist planned for November 1988. After a commissioning phase, the SIS beam will be available for physics experiments in autumn 1989, the storage ring will be in operation one year later.

The SIS is a 18 Tm synchrotron which accelerates all elements up to uranium above 1 GeV/u. The repetition frequency should be up to 5 Hz. The planned intensities per pulse range from 10^{10} for uranium to $5 \cdot 10^{11}$ for neon.

The UNILAC will be used as injector for the synchrotron. The linac is in operation since 1976. The present layout is shown in Fig. 1.

The UNILAC accelerates all elements of the periodic table up to uranium. For efficient acceleration, multiply charged ions have to be generated. The two DC pre-accelerators - shown on the left in Fig. 1 - are equipped with heated cathode PIG ion sources.

The injectors deliver the beam at the specific energy of 11.7 keV/u. The beam is pulsed at the repetition frequency of 50 Hz and has 5 ms pulse duration. Four Wideröe tanks operated at 27 MHz accelerate the ions to 1.4 MeV/u. The beam then passes a foil or a supersonic nitrogen jet. The most abundant charge state is sorted out for further acceleration in the poststripper accelerator. The first part of the poststripper section consists of four 108 MHz Alvarez tanks. The maximum energy after tank four is 11.4 MeV/u; 17 single-gap cavities can accelerate the ions to the maximum energy of 20 MeV/u.

The beam from the UNILAC can be transported to the three main branches of the experimental area. Present output intensities are typically 10^{11} particles per second (pps) for very heavy and 10^{13} pps for light ions. These intensities meet the requirements for the most experiments in the UNILAC experimental area. Also in future, GSI has to provide beam time at this place for research at UNILAC energies between 2 and 20 MeV/u.

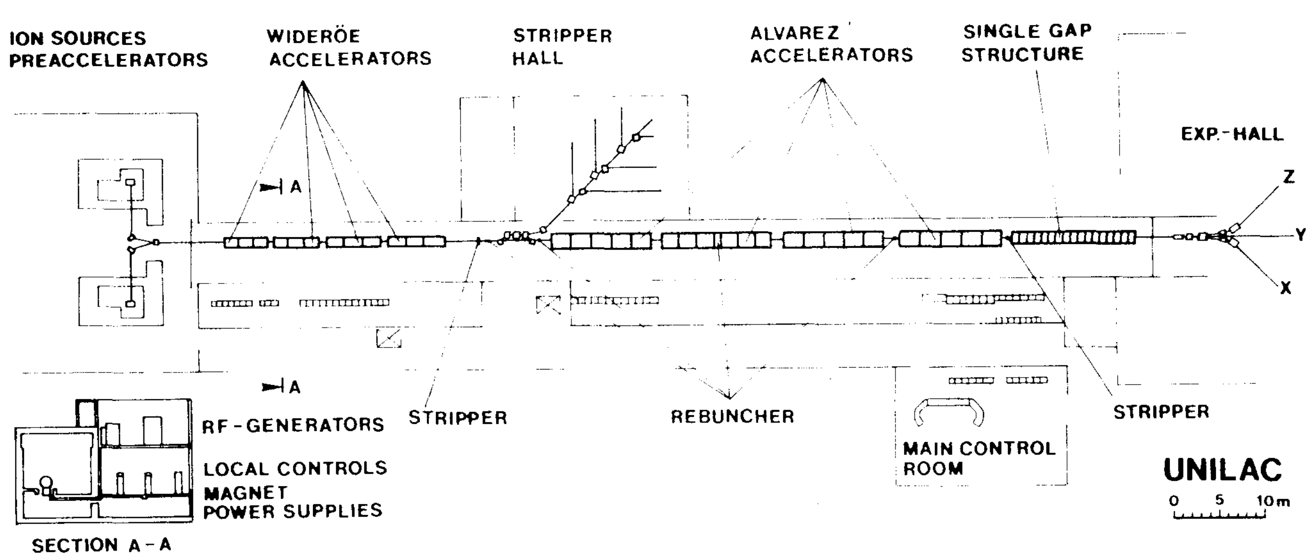

Fig. 1: Plan view of the present UNILAC

The injection time into the synchrotron is about 100 µs. Due to the reduced duty cycle, the intensity out of SIS will be in the range from 10^7 to 10^9 pps. To take advantage of the space charge limit of the SIS, much heigher intensities have to be injected - up to three orders of magnitude. This can only be achieved by an additional high-current injector.

The project of a high-current injector at the UNILAC was presented at the 1986 Linac Conference.[1] At that time, many options for the UNILAC upgrade were discussed. The most preferred version is shown in Fig. 2. The beam from a 320 kV DC preaccelerator with the high-current ion source is injected into a 13.5 MHz RFQ structure. After stripping and acceleration in a new short Wideröe tank up to an energy of 216 keV/u, the existing UNILAC from Wideröe tank 2 onwards overtakes the further acceleration. The low-intensity injector including the first Wideröe tank remains unchanged. Due to the restricted space in the tunnel, the construction is complicated and expensive. The components for beam transport and for the longitudinal and transverse matching are very costly. The design could not be optimized for the acceleration and transport of a highly space charge dominated beam, the risk for deterioration of beam quality is high.

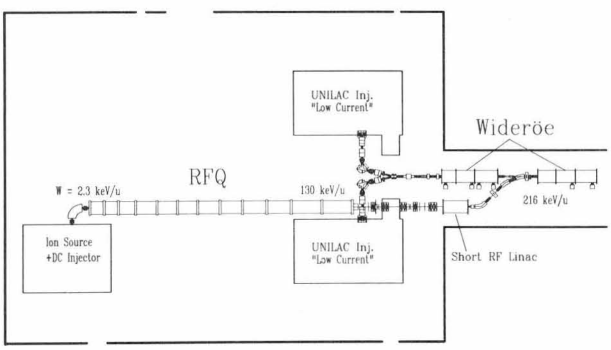

Fig. 2: Layout for injector modification under discussion

For efficient operation of the extended GSI facility, time share operation is required: beams of different ion species and currents will be extracted from the injectors and accelerated to the desired energies on a pulse-to-pulse basis. RF-systems, quadrupole magnets, switching magnets, electronics for beam dagnostic devices have to be operated in a pulsed mode. The necessary modifications are expecially very costly in the Wideröe and stripper section. More details of this project are given in Ref. 2.

The New Injector Concept

Recent improvements in the field of ion sources have been induced to reconsider the UNILAC upgrade program. The ECR (Electron-Cyclotron-Resonance)-source became operational in many laboratories. This source delivers high-charge state ions for gaseous elements and now also for metal ions.[3,4,5] The operation of the ECR-source is characterized by its high reliability. Even for high-mass elements, the intensity of ions with a charge-to-mass ratio greater than 0.1 will come to a range, suited for injection into the Alvarez section of the UNILAC without stripping. The highly charged ions can be accelerated up to the required Alvarez injection energy of 1.4 MeV/u very efficiently, the cost of this new linac is accordingly low. This linac overtakes the part of the whole UNILAC prestripper linac, which can be optimized now for high current beam acceleration avoiding restrictions of the previous design.

The revised injector project can be seen in the plan view of the upgraded UNILAC, including the transfer line, the synchrotron, the storage ring and the experimental facilities (Fig. 3). The photograph shows the extended GSI laboratory, it was taken in August 1988. The construction of the buildings has been completed.

The low-intensity, high-charge state ion injector will be installed inside the existing low-energy experimental area. At present, there a parasitic beam from the UNILAC prestripper linac is injected for experiments at 1.4 MeV/u. The beam will be injected into the UNILAC directly in front of the first Alvarez tank.

The present prestripper accelerator will be upgraded to a dedicated high-current injector for SIS injection. A new linac up to the energy of 216 keV/u is planned. The new injectors will be described in more detail in the following sections.

Low-Intensity Injector

The low-intensity injector, shown schematically in Fig. 4, comprises the ECR ion source, the low energy beam transport system, the RFQ accelerator, the interdigital H-type structure and the beam transfer line to the UNILAC poststripper accelerator. A summary of major injector parameters is given in Table 1.

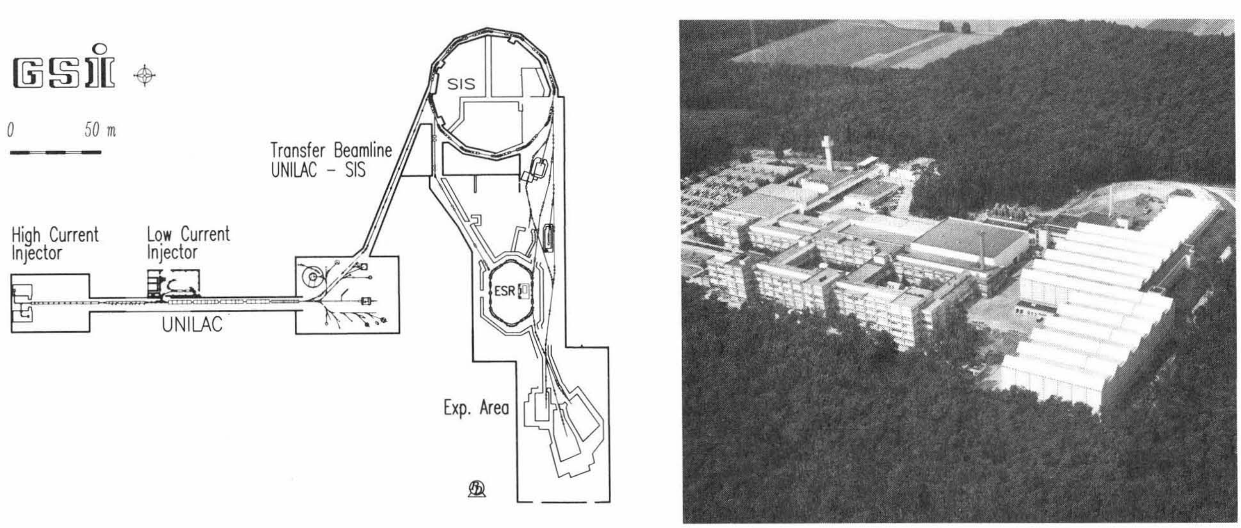

Fig. 3: Plan view of the upgraded UNILAC

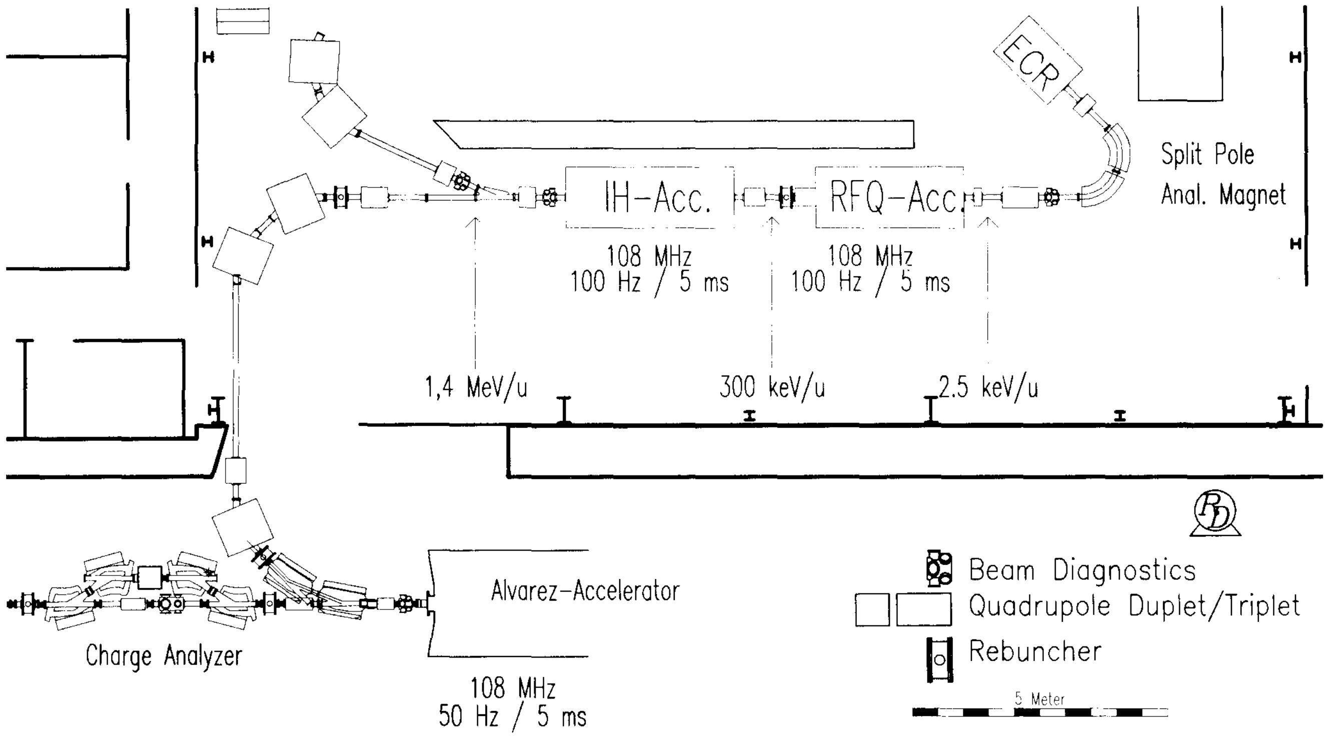

Fig. 4: Schematic of the low-intensity injector

Table 1: Summary of major injector parameters

Injection	
Ion source	ECR-type, 14.5 GHz
Charge-to-mass ratio	0.105 to 1
Extraction voltage	23.8 kV
Energy	2.5 keV/u (β=0.0023)
Radial emittance (norm.)	0.46 π·mm·mrad
Radial emittance (unnorm.)	200 π·mm·mrad
Mass resolution $\Delta m/m$	3×10^{-3}
RFQ accelerator	
Structure type	four rod
Energy, input	2.5 keV/u (β=0.0023)
Energy, final	300 keV/u (β=0.025)
Radio frequency	108 MHz
Repetition frequency	100 Hz
Duty cycle	50 %
Max. RF power (for U^{25+})	125 kW
Max. Voltage	78 kV
Length	3 m
Tank diameter	0.5 m
Radial acceptance (norm.)	≧ 0.75 π·mm·mrad
Longitudinal emittance	30 π·keV/u·deg
Energy spread	± 1.0 %
Bunch width	± 0.3 ns (± 10 deg)
IH accelerator	
Energy, input	300 keV/u (β=0.025)
Energy, final	1.4 MeV/u (β=0.055)
Radio frequency	108 MHz
Repetition frequency	100 Hz
Duty cycle	50 %
Max. RF power (for U^{25+})	100 kW
Max. field strength	150 kV/cm
Length	3.55 m
Tank diameter	0.68 m
Shunt impedance	310 MΩ/m
Radial acceptance (norm.)	1.5 π·mm·mrad
Radial acceptance (unnorm.)	60 π·mm·mrad
Longitudinal acceptance	150 π·keV/u·deg
Longitudinal emittance	70 π·keV/u·deg
Energy spread	± 0.5 %
Bunch width	± 0.3 ns (± 10 deg)

Ion Source and Low Energy Beam Transport

The ECR-source will be built by CEN, Grenoble. A research program has been started at Grenoble, in order to achieve the UNILAC requirements. The ion source has to provide high-charge state at sufficient intensities suited for injection into the Alvarez accelerator without stripping. The required minimum charge-to-mass ratio for the heaviest elements is 0.105 (e.g. U^{25+}). For gaseous elements, the ion source delivers the highly charged ions at sufficient intensities. The test results for metal ions are very encouraging - just recently 6 eμA U^{28+} were measured at CW operation with the Minimafios ion source.[6] The ECR-source was run with a 16.6 GHz klystron, the GSI ion source should operate at 14.5 GHz. Experiments at 14.5 GHz will start in spring 1989, the design goal is a current of 5 eμA for U^{28+} at CW operation.

The low energy beam transport line is designed for a transverse emittance of 0.46 π · mm · mrad, which is based on extrapolation of measurements at the oxygen injector built for CERN.[7] For charge state and mass analysis a spectrometer with high resolution is foreseen. The dipole is splitted into two 67.5 deg dipole magnets in order to minimize the second order effects by curvatures of the inner pole faces. A mass resolution of $\Delta m/m = 3\cdot10^{-3}$ for the large emittance is feasible.[8]

RF Acceleration

The RFQ structure accelerates the ions from 2.5 keV/u to 300 keV/u. The RFQ captures ca. 90 % of the beam, bunches and accelerates it. The 300 keV/u beam is further accelerated through an IH-resonator to 1.4 MeV/u. For optimum use of the new injector, the repetition frequency is increased to 100 Hz at a pulse length of 5 ms. Every other pulse can be used for low energy experiments by a fast switching magnet behind the IH-tank (s. Fig. 4).

The design and construction of the RFQ section will be done by the Institut für Angewandte Physik, University of Frankfurt. There, a four-rod design was developed, which is especially suited for low energy, low intensity heavy ion beams. A schematic drawing of a four-rod RFQ is shown in Fig. 5.

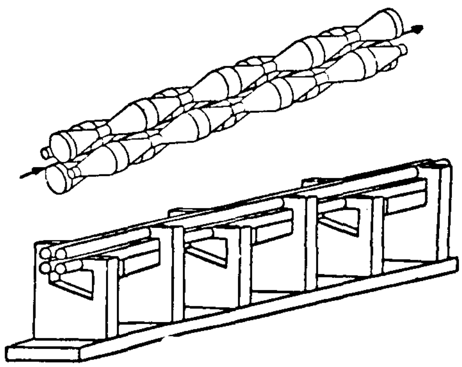

Fig. 5: Schematic drawing of the four-rod RFQ

An RFQ of this type was constructed and succesfully tested with protons, the frequency was 200 MHz. Now a second structure is under construction at Frankfurt for the Cryring project at Stockholm.[10] The parameters of the Cryring RFQ are similar to the GSI RFQ; the minimum charge-to-mass ratio is by a factor of two smaller in the GSI-RFQ, the duty cycle of 50 % is also considerably higher at the UNILAC, but the mechanical design allows the cooling of such high power losses.

The important parameters of the RFQ are listed in Table 1. The construction has been started. The structure should be ready for first beam tests at the end of 1989.

The interdigital H-structure is used so far in several Tandem laboratories to accelerate the low emittance beam behind the Tandem accelerators. The structure is characterized by its very high rf efficiency. For the UNILAC application, the radial acceptance has to be increased by at least one order of magnitude. Furthermore, the injection energy should be decreased to about 0.3 MeV/u. For the GSI design, thick drifttubes containing magnetic quadrupole triplets will be installed. Further increase of radial acceptance will be achieved by a special profile of the synchronous phase along the rf gaps. A schematic view of the IH-tank is shown in Fig. 6. Recent measurements at a 1:2.5 scaled model have shown that with proper geometry of the lense housing, the required field distribution can be adjusted. A detailed description of the IH-structure for the GSI injector is given in a separate contribution of this conference.[11]

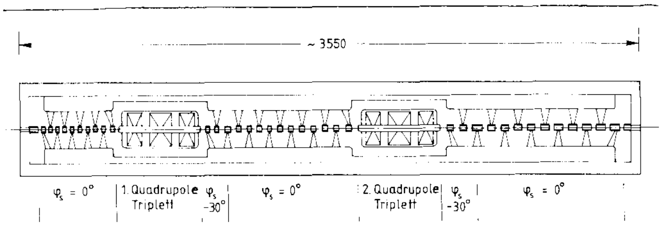

Fig. 6: Schematic view of the IH tank

The beam parameters at 1.4 MeV/u are summarized in Table 1. By proper longitudinal and transverse matching, the beam quality fullfills the requirements for further acceleration in the UNILAC Alvarez accelerator.

The design of the IH-tank has been started at GSI. The tank and drifttubes will be ordered at the end of 1988, first rf operation is planned for the late 1989.

The High-Current Injector

Concerning the high-current ion sources for the high-current injector, the statements made at the last Linac Conference[1] are still valid: The source system CHORDIS is capable of delivering high-current, high-brightness beams of a large variety of elements. For all gaseous elements, the achievable output currents can be delivered with a large safety margin. There is a need for further development of sources for solid elements, especially for U^{2+}. The MEVVA source is still a candidate for metal ions, most recent measurements at GSI have delivered better results, a high-intense Ti^{2+} beam was accelerated at the UNILAC preaccelerator and transported over 20 m in the beamline.[12]

Beam transport experiments at high intensity and low energy have shown that a very high degree of space charge compensation can be achieved, mass and charge state separation without loss of beam quality is possible, thus a spectrometer system at low energy directly behind the ion source is under discussion.[13]

Due to the experience with MAXILAC and the rapid development in the field of RFQ accelerators over the last years, it is required to consider our previous design. The MAXILAC, a low frequency (13.5 MHz) RFQ with the split coaxial resonator has been selected for the high-current injector. After 5 tanks at 45 keV/u, the design value of maximum current (8 mA Ar^{1+}) is achieved in the simulations but not in the accelerator itself, 4.5 mA Ar^{1+} have been measured. The achieved current is quite high, but not sufficient for the SIS-injector. The sources for the transmission loss are uncertain, they may due to mechanical misalignment or beam instabilities.[14] Without understanding of the behaviour of the 13.5 MHz RFQ, the structure cannot be extended to the design energy.

Changes of standard procedures for RFQ design without changes of basic parameters like electrode voltage, aperture, maximum modulation, result in higher current limits.[15] The required current of 25 mA U^{2+} can be achieved even with 27 MHz RFQ structures. This operating frequency is better adapted to the 27 MHz Wideröe structure. Due to the higher bunch frequency, the space charge forces will be decreased if the beam is accelerated in the following UNILAC accelerator sections. Calculations have also shown an improvement of beam brightness at the same current levels.

The previous final energy of 130 keV/u for the RFQ is not the optimum stripping energy for uranium, the required mean charge of 10+ can be achieved at about 200 keV/u with gas stripping. Thus an RFQ output energy of 216 keV/u - the input energy of Wideröe tank 2 - would be convenient. But there is no final decision; it is conceivable to replace the last part of the RFQ by a more effective structure like the Wideröe resonator. The use of a Fomblin stripper as proposed at Berkeley would reduce the stripping energy to about 120 keV/u, a short Wideröe tank would accelerate U^{10+} to the injection energy of Wideröe tank 2. But the behaviour of Fomblin at high-current beams is unknown, experiments are necessary.

The basic parameters for the new design of the high-current injector are listed in Table 2. Meanwhile, first RFQ design studies have been carried out.[16,17] At 27 MHz, an alternative structure to the split coaxial resonator was developed at Frankfurt.[17] A schematic view and a photo of the proposed four-rod structure with spiral shaped stems are shown in Fig. 7.

Table 2: Basic Parameters of the High-Current Injector

Energy, input	2.4 keV/u
Energy, output	216 keV/u (120 keV/u)
Frequency	27 MHz
Repetition frequency	1 - 5 Hz
Pulse length	≦ 1 ms
Charge-to-mass-ratio	≧ 0.0076
Current limit	≧ 0.2•A/ζ emA
Max. voltage range	2 - 2.5 Kp
Length	ca. 35 m

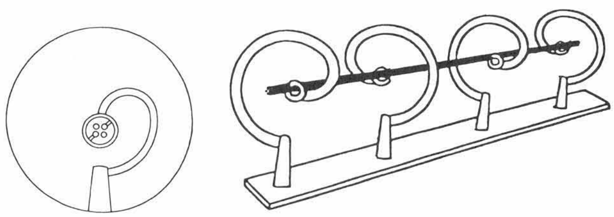

Fig. 7a: Scheme of spiral RFQ

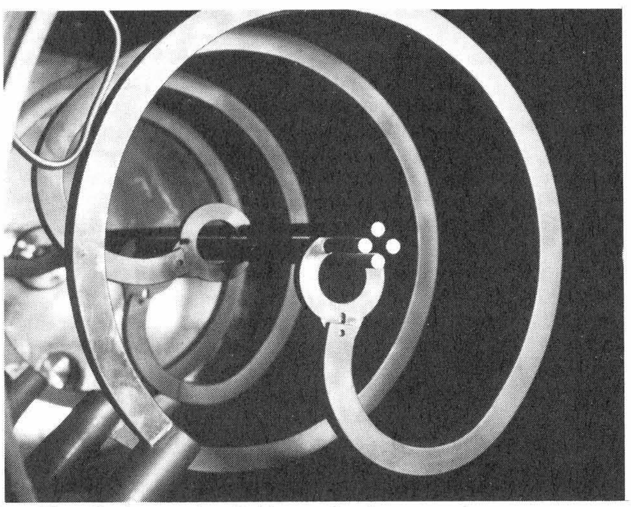

Fig. 7b: Photograph of the spiral resonator

A short power test modul was built for sparking tests. At short pulses the sparking limit is sufficient high, at present no sparking occurs at 3 times the Kilpatrick value. Further sparking experiments are planned. A prototype of a four-rod RFQ will be built, high-power test and beam measurements should prove the capability of this structure.

Modification of the Postaccelerator

The UNILAC poststripper accelerator has been modified for time sharing operation at 50 Hz.[2] The goal is to deliver on a pulse-to-pulse basis independent beams of different ions, currents and energies. This is accomplished by the use of a number of strategically placed pulsed quadrupoles and steering magnets, and by pulsing the rf gradients and phases. The beam diagnostics and the control system have to provide selective evaluation of each pulse.

During regular shut-down periods, 30 laminated core quadrupoles, 20 steering magnets and their pulsed power supplies were installed. Modifications of the rf control, beam diagnostic electronics and computer control system has been started. Energy switching of the same ion species will begin in 1989. The new injector concept allows an easier and cheaper solution for ion switching: Changing ions can be provided by switching between the injectors.

Schedule and Cost Estimate

The new components for the low current injector should be on place at the end of 1989. The first operation is planned for the beginning of 1990. The R&D phase for the high-current injector will be continued until the end of 1989. Then a final design should be available. The estimated construction time will be two years.

The total cost for the low-current injector would be 6.3 Mill. DM, but a significant cost saving can be achieved by use of existing components, e.g. quadrupoles, bending magnets, power supplies, and two rf transfmitters. The total cost saving is about 3.5 Mill. DM. The cost estimate for the high-current injector is difficult at present as there is no final design decision but the cost of the previous version - 8.5 Mill. DM - will be decreased at least by 3 Mill. DM due to the new concept. Thus the total cost for both injectors of ca. 8.5 Mill. DM will be unchanged. Additionally, ion switching is possible without extra cost.

Acknowledgements

The work reported in this paper is the result of an effort by many members of the UNILAC group. The fruitful colaboration with the Institut für Angewandte Physik, Frankfurt, and with the Centre d'Etudes Nucléaires, Grenoble, is gratefully acknowledged.

References

[1] J. Klabunde et al., The Project of a High-Current Injector at the UNILAC, Proc. of the Lin. Acc. Conf., Stanford, 1986, SLAC-Report-303, p. 299
[2] J. Glatz, The UNILAC as a Fast Switching, Variable Ion and Energy Accelerator, Proc. of the Lin. Acc. Conf., Stanford, 1986, SLAC-Report-303, p. 302
[3] R. Geller, B. Jacquot, Sources for Highly Charged Ions - the ECRIS Status, Proc. of the Lin. Acc. Conf., Seeheim, 1984, GSI-84-11, p. 31
[4] B. Jacquot et al., Source d`ions lourds CAPRICE 10 GHz 2 ω_{ce}, NIM A 269, 1988
[5] R. Geller, ECR Sources, Status and Recent Developments, These proceedings
[6] R. Geller, Private Communication, Sept. 1988
[7] B. Wolf et al., Heavy Ion Injector for the CERN Linac 1, NIM A 258, 1987, p. 1
[8] L. Dahl, T. Schwab, Analysiersystem hoher Auflösung nach der EZR-Quelle, GSI-UNILAC-INT./88-3, 1988
[9] A. Schempp et al., A Light Ion Four Rod RFQ Injector, Proc. of the Part. Acc. Conf., Washington, 1987
[10] A. Schempp, H. Deitinghoff, H. Klein (Frankfurt), and A. Källberg, A. Soltan, C.J. Herrlander (Stockholm), RFQ-Injector for CRYRING, Proc. of EPAC, Rome, 1988, In press
[11] U. Ratzinger, A Low Beta RF Linac-structure of the IF-Type with Improved Radial Acceptance, These proceedings
[12] P. Spädtke, H. Emig, J. Klabunde, D.M. Rück, B.H. Wolf, I.G. Brown, High Current Metal Ion Beam Transport in the UNILAC Injector at GSI, GSI Report, GSI-88-20, 1988
[13] J. Klabunde, A. Schönlein, R. Keller, Isotope Separation Experiments with High Intensity Ion Beams at Low Energy, GSI Scientific Rep. 1987, GSI 88-1
[14] R.W. Müller et al., Status of RFQ Linac MAXILAC, GSI-88-17, p. 21
[15] A. Schempp, Design of Compact RFQs, Proc. of EPAC, Rome, 1988, In press
[16] A. Warwick, A 27 MHz Alternative to MAXILAC, GSI-UNILAC-INT/87-2, Int. Rep., 1987
[17] A. Schempp, H. Deitinghoff, A. Kipper, 27 MHz Heavy Ion Spiral RFQ Development, Proc. of the Fusion Workshop, Darmstadt, 1988, In press