THE UNILAC, DEVELOPMENT AND PRESENT STATUS

D. Böhne

Gesellschaft für Schwerionenforschung mbH
Darmstadt, Fed. Rep. Germany

Summary

During the year 1975 the Unilac heavy ion linear accelerator was completed and stepwise put into operation. The paper summarizes the operating experience obtained so far and compares the performance of the different systems and of characteristic technological details on the basis of the original design concepts.

Introduction

Starting in spring of 1975, the prestripper accelerator of the Unilac was in operation for low energy (1.4 MeV/u) experiments, and machine studies in the poststripper at the Alvarez energies of 3.6 and 5.9 MeV/u were done in parallel. During the autumn shut-down in 1975 the single gap cavity section had been added, and debugging went on late in 1975. In total, the completion of the machine was nearly one year behind schedule due to late deliveries of components. In January 1976 the Unilac began its routine operation with heavy ion beams for fundamental research in nuclear physics, nuclear chemistry, atomic and solid state physics. In this year, until the annual shut-down in the mid of August, about 1000 target hours were obtained for survey experiments in the field of medium and heavy mass numbers and variable energies up to 7.5 MeV/u. During this period, much time was devoted to bring up the subsystems of the accelerator to the design specifications and to an acceptable reliability. Intense machine studies have been postponed until a definite status and an improved reliability of the subsystems will be reached and until adequate measuring apparatus and evaluation methods for energy spread, bunch structure and beam emittance are available.

Since the Unilac project has already been presented at several occasions in this conference series (1.2.3.4), a general description of the machine will be omitted here. Special parts and subsystems of the machine, which are new or typical for a heavy ion linac are described in different papers of these proceedings (5.6.7.8). This paper actually reviews aspects and difficulties of the construction phase, and argues critically about how things came out compared to the original ideas and finally outlines changes and improvements which await to be done.

The Injection System+

Proton machines and heavy ion machines are intrinsically different in the injection system. At medium energies, say at a couple of MeV or, rather, at a couple of MeV per nucleon, they become similar as far as linac technology is concerned, and at high energies the difference vanishes.

In the last decade two ambivalent developmental lines have demonstrated considerable progress: In one field, existing proton synchrotron facilities are pushing source development in the low mass number regime, in order to obtain almost completely stripped nuclei. In the other field, the heavy ion people tend to be pessimistic about a near future success of those novel source concepts, intended to provide extremely high charge states. They prefer to live with available source schemes and concentrate on an accelerating system which complies with the quite poor charge over mass ratio of heavy ion beams obtained from sound and proven source concepts. The Unilac is a vital example of the latter school.

At the time the Unilac study group was established in the early sixties and experimental activities began, source development and stripping measurements clearly had to be attacked to provide fundamental data for the design of a new heavy ion linac.

The measurements of equilibrium charge state and charge exchange cross sections as a function of particle energy was performed on tandem Van-De-Graaff facilities and a semi-empirical law was found allowing a decent extrapolation of the stripper performance for higher energies. Thus this subject was well covered in a few years.

In the field of ion source research the same academic procedure - taking measurements, finding a theoretical model or fitting an empirical formula allowing for reliable extrapolation - never worked out. Since a rough estimate revealed that a 10 % increase in charge to mass ratio at the same particle current abundance for heavy elements would result in a one Million Mark saving for the linac, the justification for an appropriate source research effort was evident. The linac design had to go ahead and therefore it was urgent to freeze such basic parameters like minimum charge to mass ratio, influencing machine length and cost. Test bench data obtained for rear gases in Berkeley and Dubna served as reference.

Those data, eventually obtained in test bench measurements and not on a real injection system, have been used for an speculative extrapolation, resulting in output intensity of a couple of particle micro amperes for uranium in the charge state of 11+. Since then this minimum charge to mass ratio was used as the lower limit for the design of the injection system and the prestripper linac. Since the frame of machine parameters was set up, the developmental activity of the source group was reoriented trying to reproduce data obtained from elsewhere and to a concentration on operational characteristics, like lifetime and equipment reliability. The search for

+For details and Figures see ref. 5.

new source concepts went on at three associated universities, sponsored by the GSI until the mid seventies. But the drastic breakthrough in the search for a useful, novel source did not occur.

Today the situation is as follows: The original extrapolations were found to be wrong by one order of magnitude according to new test bench measurements, and they are even worse by another factor when the really useful intensity at the entrance of the linac is quoted. Fortunately injector high voltage, beam transport parameters and the rf power for the prestripper have been planned with some reserves in their maximum rating, however for a different reason, namely, to assure equipment reliability. Thus it is now possible to accelerate uranium 9+ and eventually even 8+ instead of the design value of 11+. In addition the majority of machine users tend to be satisfied with a beam intensity 10 times less than originally envisaged.

Presently the same amount of man power in the laboratory is active in the field of ion sources, as it was in the past 10 years. But it concentrates more on expanding the variety of available ion species and on reliability improvements rather than on progress in high charge state abundance.

Another feature of the Unilac, more progressive than the before-mentioned application of known ion sources, is the provision of two identical injectors. Though this is the rich man solution of the lifetime problem encountered with heavy ion sources, an important fraction of the machine time is presently lost due to ion source and injector failures and the necessity of a subsequent retuning of the whole machine. This curiosity is temporary rather than of fundamental nature: Actually, both injectors have been built and have been equipped with a duoplasmatron installation. Injector south also got a complete PIG source installation and the duplication of this source type in injector north was delayed until an indefinite date. As two insulating transformers were lost for some unknown reason, the remaining two transformers were used one for the DP source in injector north and the other in injector south for the PIG source, hence excluding the envisaged stand-by operation of a second DP source.

Summing up the operating experience of the past year, the original philosophy of having a stand-by duplicate for both sources was reestablished. It is not simply the lifetime of the source itself which determines the downtime. Break downs of the auxiliary supply equipment in the terminal or in the injector system contribute significantly to the loss of beam time. Thus in 1977 both injectors will be recompleted with a DP terminal and a PIG source terminal in each.

A third important difference between the Unilac injection system and other linac injectors is the typically low injection voltage of about 250 kV, the maximum ratings being 320 kV. Bearing in mind the short lifetime of a heavy ion source and the reconditioning time law versus gap voltage, a low accelerating potential was favoured. At that time a rotating shaft motor generator rated for a terminal power of 50 kW was not recommended by the supplier. The alternative, an insulating transformer, however, was supposed to be restricted to about 300 kV. Both statements appear obsolate today.

Since a completely novel prestripper accelerator structure had to be conceived even for a somewhat higher injection voltage, a standard 750 kV high tension installation would have saved only three gaps in the prestripper linac, however, the most critical gaps. A pressurized injector with a few MV potential never seriously was considered.

Today the fundamental argument for the low preacceleration voltage, namely the immediate and rapid acceleration of the extracted beam, requiring a compact source installation inside the column, is no more found to be substantial. A development is underway to isolate the vacuum of the accelerating column by a valve and to compensate for the space charge effects by focusing elements placed between source and accelerating gap. In this case a reconditioning of the accelerating column is no more mandatory and the gap voltage could have been chosen independently. However, cost and space considerations substantiate the choice of moderate voltage in the case of a duplicated injection system, because energy gain in the prestripper linac is less expensive.

In conclusion:

1. The duoplasmatron source now has a satisfactory lifetime also for heavy ion application, predominantly for gasous elements (no compounds). It is inexpensive, shows a low emittance and an excellent stability. The hot cathode PIG source generally is capable of higher beam intensities at high charge states but at the expense of an equally higher emittance. Its performance for metallic elements, introduced in the arc volume by a sputter electrode, is satisfactory. The question, however, whether really two source types are necessary to cover the whole variety of elements is still unresolved. Developments are underway for the DP source, aiming at a still more abundant ion output for higher charge states and aiming at an application for metallic ions too. And developments are going on improving the stability, the emittance and the reliability of the PIG source.

2. Two separate preinjectors are really recommended for a heavy ion linac. The source lifetime being not the predominant argument, rather than the tune up time for a different ion species or a different isotope beam.

3. The high voltage potential should be chosen according to space and cost considerations; somewhat between 300 and 500 kV would be a good value. However, the ratings of the preaccelerator, the beam transport and the prestripper linac should comply with the lowest charge over mass ratio. Sometimes the source output is poor and the selection of a lower charge state is advisable.

The Linac Structure+

It should be reminded that for a heavy ion machine, with uranium as the heaviest element, a preinjector voltage of 16 MV would have been required to obtain an equivalent injection particle velocity as it is usual in the 200 MHz proton linac concepts. The restrictions of a pressurized heavy ion preaccelerator are not acceptable for various reasons, and a tandem Van-De-Graaff injector was ruled out because of its high cost and low beam current capabilities. Thus the heavy ion linac designer is bound to step down in frequency for a prestripper rf-accelerator, and the traditional and passionate search for the optimum structure began once more. But except for the Wideröe structure, there was not much choice in the low β-region, say at $\beta = 0.005$ and a freqency of 27 MHz, because an Alvarez cavity would have become unduely large in diameter. During a period of one year, however, after authorisation of the project, everything had been reconsidered to save the Alvarez structure at an acceptable frequency of about 100 MHz. Raising the injector voltage to 1 MV was considered, the drift tube configuration was changed to a 6 π mode, the radial acceptance was lowered tentatively. Every combination turned out to be unduly marginal, even for the ambitious charge state of 11+ for uranium.

Hence the venture of a completely novel structure, a coaxial Wideröe structure with a strong focusing element in every second drift tube was agreed upon. Nearly everything which is today recommended not to be done in high vacuum technology had to be incorporated into the structure: Water joints, inaccessible vacuum joints, non-inspectable high current contacts, elastomer rings, bolts and nuts. Instead of a full-scale power model, tank number 4 was drawn ahead in the time schedule by one year for high power experiments, so that changes could be applied in the case of prohibitive multipactoring, hot spots, contact burn out or warping of the center conductor.

Nothing of that intense check out program could be done, because the last couple of drift tubes arrived one and a half years behind schedule. This catastrophe about the Wideröe drift tubes, actually a lengthy story about OFHC and the common market, led to a valuable discovery: Missing quadrupoles are not so inhibitive for a perfect beam transmission in a drift tube structure, than the purism of straight forward beam dynamics calculation would suggest. Bead pulling measurements and even beam acceleration in tank 1 was successful with only two thirds of the actual drift tubes, the rest was replaced, for some time, by poorly aligned aluminium dummies. Still today, when a drift tube develops a leak, a simple dummy is installed and no degradation of beam transparency is measurable. Presently 5 dummies are in the structure (sometimes it was hard to know, how many) and they will be replaced in the next shut-down period. Actually all the stem bellows, which are water cooled because of the high current density on the drift tube stems in this structure, have to be replaced sometimes. The bellows are made from double sheet metal copper, and if the cooling water enters by a virtual leak between both walls, spot corrosion takes place and perforates the outer wall. The detection of such a leak is simple: A white spot of salt deposit is visible on the vacuum-side surface. Another accident, predicted to develop on the bellows, never occured: In spite of a supplementary electro-plated reinforcement of the very soft copper, the water pressure deformed the bellows and corrugations got in touch to each other forming undefined current contacts. However, no sparking tends to occur.

Except for a discouraging multipactor behaviour encountered during the initial turn on, and except for the above-mentioned bellow situation, no further break down occurred so far on the Wideröe structure. Listening to the operators, it has the reputation of being the most convenient and reliable part of the machine. It is now not the least problem to turn it on, to focus the beam through, to set the right phase and amplitude values, to get the correct energy out and to obtain an almost perfect beam transmission and stability.

The Alvarez structure, the most important part of the 108 MHz post stripper accelerator, has been built as designed, parts have been delivered on schedule and the assembly and turn on was simple. However, both tanks have not received full rf power due to deficiencies of the rf amplifiers. Except for the rf window, which will be discussed later, no failure or malfunction occured so far. Also the turn-on and tuning of the rebuncher cell in the mid of tank 2 was easy, refocusing the bunch structure at the entrance of the following single gap cavities, if tank 2 is switched off for a coarse step energy variation.

Few mechanical engineering details should be reviewed, which are different from the standard Alvarez design: Since the cavity consists of several mild steel, copper plated subsections bolted together, an accurate machining of the inner diameter (about 2 meters) was possible and also a slightly tapered diameter over the length could be applied without additional cost. Thus the G/L ratio of 0.25 is kept constant over the whole length of 24 meters for both cavities, avoiding the requirement of a field tilt. The LALA computations (obtained by LASL) were used for electrical parameters like shunt impedance, and precision cell model measurements were carried out for determing the geometrical dimensions. The accuracy of the actual tank sections has been such that the frequency came right on in the 10^{-4} region. No tuning bar was necessary to adjust the frequency or the field flatness in tank 1 and in the two halves of tank 2 (a rebuncher cell is in the middle of tank 2). The frequency drift from zero power to full power is modest, four tuning slugs per cavity are sufficient, 12 slugs had been provided initially. The scheme, having the stem bellows outside of the rf field volume, was successful, and the twin-stem design of the drift tubes provided a mechanically stable system, also allowing for a convenient adjustment.

The two groups of 10 single gap cavities each, follow the Alvarez structure at the high energy end. The half drift tubes are manufactured from copper and have got aluminium caps to reduce the x-ray flux, generated by the field emission electrons. All the other pieces, like outer cylinder, rf end walls, tuning slug and drive loop have been

+ For details and Figures see ref. 4 and 6.

made from mild steel and have got a copper plating. The spiders, in between the cavities, first have been made from iron castings. Though there is only a soft vacuum maintained between two adjacent cavities, the porosities of the spiders were significant and nearly all had to be replaced by steel castings.

The scheme of such a cavity chain leaves not much choice to the designer with respect to access and ease of repair. For several times it was necessary to fix water leaks in the soft vacuum volume between two cavities. In this case it takes 5 days to take the cavity chain apart in one particular plane and bring it back together.

In one important parameter, the cavity design did not meet the specifications: The thermal runaway of the resonant frequency is twice the value that can be compensated for by the slug tuner, thus only about 25 instead of 50 kW average rf power can be applied. It is believed that this detuning results from a temperature gradient in the 7 mm thick steel rf end walls, which tend to warp and execute heavy forces on the supporting spiders and subsequently deplace the half drift tubes. This effect will be studied on a test cavity and the end walls will be modified either by removing their stiffness by cutting several groves in the steel plate or by replacing the whole design in favour of a thin copper sheet metal with soft soldered cooling channels on the rear side.

Another subject, related to the single gap cavity design, deserves some comments. Though the quadrupoles inside the half drift tubes can be adjusted from outside, they had not been aligned after the assembly of a complete cavity chain, relying simply on a mechanical centering in the assembly stage. Actually there is some evidence of an intolerable misalignement, because the beam, centered at the entrance of a chain, wanders significantly with quadrupole excitation. This must be checked out, but it is not quite clear how an optical target can be inserted in the beam tubes, because there is no straight manual access to it.

A few aspects, which are relevant to all structure principles used in the Unilac, shall be mentioned finally:

Ten years ago, there was much concern about rf break down in linac gaps. The Unilac is another example, where sparking was never a problem, though the average gap gradient is 17 MV/m in the single gap cavities. Presumably this improvement came with the clean pumping systems and all-metal seal techniques used today.

It is still a question of purism for the linac designer, to what an extend one should insist on the metal seal philosophy, since the argument of baking does not apply to a cavity structure. In the Unilac the all-metal technique has been applied to an extreme extend, the gate valve seals and a temporary rf window in the Alvarez are the only organic materials exposed to the vacuum. Conflat flanges are used for the beam transport lines, beam diagnosis boxes and for every external equipment flanged to the cavities. The knife-edge seat has been machined directly into the mild steel cavity walls, special care has been taken in choosing the tolerances accounting for the copper plated deposits. All other vacuum joints, nearly one thousand, which are not of standardized dimensions, like cavity joints, drift tube flanges etc. are sealed by a gold wire. Preference was given to gold wires instead of aluminium in case of a simultaneous rf joint, because it was experienced at different occasions that the Q value deteriorates with time if important rf contacts, like end walls and subsections of a cavity, have been sealed by aluminium wires. A technique was found to gold plate an aluminium wire, but it seemed not to offer a significantly less expensive solution. Only in one case, on the short circuit plane in a Wideröe stub line, such a rf contact failed occasionally. However all main seals between the Alvarez tank one sections developed a small, but tolerable vacuum leak, because this tank was occasionally operated without cooling. On the single gap cavity group number one, on which an operating time of about thousand hours was accumulated, 12 main seals became leaky. However those small leaks never prevented a continous operation. Thus the generally introduced precaution of a backing vacuum behind every wire seal proved necessary. In addition, this double seal, with an elastomer ring on the atmospheric side, was very advantageous in the assembly phase, allowing for an individual leak check of every wire gasket when a leak detector was connected to the backing vacuum volume.

An important property of the cavity technology in the Unilac is the resolute application of the copper plating technique for every surface exposed to the rf fields. Only the drift tubes are made from solid copper material. The selection of the plating technique is derived from the fact that 10 years ago no manufacturer could be found in Germany, who would offer a cavity fabrication based on copper clad material. A small quantity of this material for a prototype cavity could not easily be procured. On the other hand, the hardness of carbon steel as bulk material offered excellent properties for an all-metal seal concept favourable both for ultra high vacuum and for reliability considerations of high current rf contacts. The possibility of machining relevant cavity dimensions, the simplicity of welded cooling channels and finally the existence of competent commercial plating companies contributed to the decision. Though there was a successful cooperation with industry in the prototype phase, it finally turned out that no plating shop could guarantee the specified quality in respect to surface roughness and electrical conductivity in a series production treatment of cavity dimensions, which were beyond the usual standards. GSI had to take over the plating treatment of about seventy cavity sections and of about 80 rf end walls, and about one thousand smaller pieces were plated as fill-in activity. There is no doubt that the whole venture was successful. Very few pieces had to be plated a second time or had to receive a repair plating on a limited area, where the copper deposit did not stick to the steel. The measured Q value of the cavities actually reached 95 % of the theoretical figure, the surface was excellently smooth and conformed to the requirements imposed by the wire seal and by the knife edge seal principles.

No damage occured to the copper surface neither in the assembly phase nor under rf power operation.

Evidently there remains the question to be answered, whether the plating approach is recommended as a worthwhile alternative to the copper clad design. Even assuming the situation that the plating plant and the technological knowledge is not readily available, the answer is still "yes" for a linac equal in size or greater than the Unilac. The only disadvantage of the plated steel version of long linac cavities is the fact that the depth of the bath countainers and the building height is limited to some extent, so that more shorter tank sections have to be bolted together requireing an expensive seal, which, however, will never be opened again. That objection is partly true for the Unilac. It should be mentioned, however, that copper plated steel cavities can be copper welded together in place, if an underlay copper weld is applied to the cylinder ends prior to the plating process. This solution was investigated on a small test cavity, but the result came too late for a design change of the Unilac cavities.

A satisfactory solution exists for the rf windows of the Unilac cavities for neither one of the three different structures. Unfortunately any approach which has proven to be successful in one machine must not necessarily work out for a different geometry, different frequency and power level, since discharge phenomena depend on those parameters. The problem seems to be aggravated in high duty factor machines and in an environment of a high x-ray level.

Since a ceramic disc window failed on an early test cavity ten years ago, it was replaced by a dome window. This alternative proved to be satisfactory and was in operation for several years, however, at 3 % duty factor only. This solution was adopted for the single gap cavity structure and on a prototype cavity the dome windows developed pinholes after about one hundred hours of operation. A surface coating on the vacuum side cured the problem, no puncture of the ceramic occured during a test run of about 1000 hours at 180 kW pulse power and 25 % duty factor.

For the final installation on the single gap cavity structure, a different manufacturer got the order, applying a different coating and the failures reoccured after several hundred hours. An inspection of the ceramic surface revealed that the tin oxyde coating had disappeared. A new test series is underway, aiming at a more resistant coating, reducing the secondary emission factor. A disc window design, adopted from the DESY storage ring, is equally under investigation. Also the small domes, used for the pick up loops in the tanks, which never have failed in the prototype cavity, now regularly develop leaks through the ceramic. In this case a titanium coating could be used, since the domes do not penetrate into a significant electrical field. After this treatment, the problem seems to be cured for the small domes.

In the Wideröe cavities, domes are in service for the drive loop since one and a half years without any appearance of vacuum leaks. In tank 4, where 0.52 MW are coupled into the cavity via a 150 mm opening, the loop on the atmospheric side tends to arc and the dome imploded as a consequence. In this case a pressurized drive line is supposed to avoid the arcing, if not, a second drive line must be installed in future.

For the Alvarez cavity, no manufacturer for a dome window could be found initially because of the large dimensions of the ceramic piece. There a rexolite window was used in the 30 cm diameter coaxial line. This window developed severe arcing on the vacuum side at a small fraction of the design power, spoiling the cavity by organic deposits. Subsequent sparking in the drift tube gaps damaged the copper surface significantly. A new window, with deep corrugations cut into the rexolite disc, shifted the discharge level somewhat up, and arcing also occured on the atmospheric side. After the installation of a new window of the same design with a slight nitrogen flushing on the outer surface, operation was possible for half a year at one third of the nominal power level. After a recent inspection, discharge traces have been found on both sides. In the meantime a dome window has been procured. The power level could be raised to half the design value, then the vacuum pressure went up, presumably as a consequence of the dirty copper surface, spoiled by the above-mentioned window arcing. It is not clear at the present time, whether the dome will stand higher power levels and how long it will last until punctures may occur. In parallel, a redesigned loop with a brazed ceramic disc window, placed in a different distance from the coupling reference plane, is presently procured and the drive lines are going to be duplicated in order to reduce the arcing risk.

The RF System

Compared to proton and heavy ion accelerators built so far, the Unilac has a fairly complex rf system. It consists of four identical 0.5 MW amplifiers for the prestripper at 27 MHz, two 1.6 MW amplifiers for the Alvarez cavities and twenty 0.18 MW amplifiers for the single gap cavities at 108 MHz. Five additional 0.18 MW amplifiers are in service for two rebunchers, one debuncher and both drivers for the Alvarez power stage. All amplifiers are pulsed on a low power level,the conceptual ratings allow for a 25 % duty at full pulse power level.

Except for the before mentioned five individual systems, mostly unified 1 MW plate power supplies are used, one for the prestripper, one for the Alvarez amplifiers each, and one for each group of 10 single gap cavities. The scheme of common DC supplies for several amplifiers was not substantiated by technical reasons rather than by cost saving considerations. Thus it was possible to avoid step down transformers, the associated switch gear and heavy cabling for 5 MW on the 380 V line, the line voltage of the five large power supplies being 20 kV. There was no disadvantage found so far of feeding the system directly from the 20 kV mains, because vacuum contactors on the primary shut off the mains power in about 10 msec in the case of a crowbar event. In one case, however, a vacuum switch failed and the complete mains network including the substation of the power company was shut-down. Vacuum contactors therefore receive now regular inspection. The question, however, whether it is tolerable to shut off a multiple amplifier system in the case of break down in one single amplifier tube, depends on the turn-on characteristics of the cavities. In the situation of the four Wideröe amplifiers, they come right on by pushing four buttons after a tripp off of the common plate supply. For a single gap cavity chain, it may take half an hour to bring all cavities back to the operating power level, since the frequency runaway is too large for an instantaneous tracking of the resonant frequency control. This situation must be improved anyhow in future.

Another feature, characteristic for all rf amplifiers of the Unilac, is the amplitude control scheme. It should be remembered that for a heavy ion linac the rf power must be variable by 10 to 13 dB according to the charge over mass ratio of the ion species. In this case it seemed advantageous to regulate the rf anode voltage swing of the final amplifier to a constant level, the output power being adjusted by means of a movable output coupling on the plate cavity. This constant plate voltage scheme provides the utmost plate efficiency independent of the power level in the accelerator cavity and simplifies the control loop characteristic. Actually this scheme depends on a perfect impedance match. Since the anode rf voltage is kept constant, any load impedance instability in the plate circuit results in a power fluctuation in the accelerator cavity. Instabilities of the load may result from minor linac cavity detuning, since the resonant frequency control certainly has a residual error. In practice, intolerable beam fluctuations have been observed to be correlated to the slug tuner action in Alvarez tank one. This will be cured by either improving the loop gain of the resonant control, or, what is deemed more adequate, by closing the amplitude control loop via the tank pick up loop.

Phase control loops have never presented a problem; the envisaged tank phase stability of ± 1 degree seems to attainable. A gating of the phase loop during the risetime of the cavity may be introduced later, to avoid an interference between amplitude and phase control during the filling time, resulting in loop ringing in the case of a slight cavity detuning.

The major problem with the Unilac rf system, which still persists in spite of a considerable development effort since 5 years, is the power limitation of the Alvarez amplifiers, as a consequence of parasitic oscillations in the high power tetrode. This situation limits the beam current intensity for very heavy ions and the system reliability as well. A reduced duty cycle and foil stripping had to be used so far for xenon and heavier elements. About 16 tubes became defect and had to be returned to the manufacturer. And for some periods a damaged tube had to be used with only 12 % of the nominal output, since no spare was available.

This high power tetrode, rated for 1.8 MW pulse and 0.5 MW average power at 108 MHz, was specifically developed for the Unilac, based on an available tube family, used in short wave communication transmitters. It is well known that very high frequency tubes with considerable geometrical dimensions show the tendency of higher mode oscillations inside the tube structure, if such a tube is put in a perfectly shielded envelope. This is not an accidental malfunction of the particular tube design, it is rather a generally observed, though poorly understood phenomenon. The more or less successful remedy against those parasitic oscillations is an empirically found attenuating device introduced into the input and output cavity circuit. Damping provisions of various nature have been applied to the anode circuit with questionable success. A trivial approach is the reduction of the filament power at the expense of reduced power gain. The tendency to those instabilities appears to be extremely different from tube to tube, and a noisy tube in one amplifier may turn out to remain stable in another, almost identical amplifier.

Curiously those tubes, which already went off by a grid to cathode short, and which tentatively have been submitted to a high current burn off cure, became decently stable thereafter. Also a long-term improvement of the stability is observed. Since things are poorly conclusive so far, a test bench program will be resumed shortly. In the meantime a duplication of the amplifiers is nearly complete, thus the so-far-obtained reduced power output of the present tube choice may be a situation to live with.

Linac Operations

It is clear that a universal heavy ion linac requires much more tune up effort than a proton machine. Every day, sometimes several times a day, beam parameters have to be changed according to the users' requirements. In addition, a source change or sometimes a minor adjustment of the source parameters requires a subsequent retuning of the linac beam transport elements. Hence there is much concern about the fact that presently still one quarter of the switch-on time of the machine is lost by tuning activities. Another quarter is lost by source break down and source maintenance and by other equipment malfunctions as well. There is a strong interference between both categories: The majority of equipment failures occur during tune up. In total, 50 % of the machine time is useful as target hours. Though there was a continuous effort to improve this factor, statistics of the last eight months revealed that the tune up time roughly remained constant, and the sources for equipment failures fluctuate such that no particular improvement program would clear the situation, except for a few trivial deficiencies.

It is poorly understood so far, why set values, obtained once in a manual optimisation effort, are barely useful as start up basis for a next run, aiming at exactly the same particle beam. Under these circumstances the computer control aid is questionable, unless programs for an iterative optimisation are implemented. However, this goal was considered to be a second step in the computer control philosophy.

In a start up phase of a new machine, nearly every piece of electronic equipment is subject of individual modifications, and many systems are in a steady improvement process, excluding temporary and unsatisfactory components. And it must be guaranteed as well that every subsystem is brought back to its initial status after routine inspections.

This phase has clearly to be brought to a definite end, until any effort of understanding the machine can be expected to provide conclusive results.

The present strategy is twofold: In a shut-down period all analog values of the machine, which are of relevant influence to the beam, must be checked out in order that every magnet power supply or phase shifter reacts precisely and reproducibly on the command signals, and every metering device and beam diagnostic element really reads a true value. A more difficult undertaking is the search for instable alignments and fluctuating shorts in in quadrupole coils.

In a second effort, a routine emittance read out will be established and the beam transport elements of the injection beam lines will be adjusted such that a standardized emittance pattern is obtained at the entrance of the prestripper linac. Thus a successful and reproducible result of the preadjustment of all machine parameters is expected.

The present situation is as follows: An operating crew consists of a shift leader and two operators. When the machine is turned on, or when a different particle should be accelerated, the operators enter the beam parameters into a display console and obtain printed lists of set values, which have been derived by the computer out of a stored file of beam dynamic calculations. Those values, called "theoretical" values, generally provide the best basis for start up. While the ion source is turned on - it takes a couple of hours to tune the source and to identify charge states and isotopes - the operators set all switches and potentiometers according to the printed data and check the status of the total equipment. If a sufficient intensity is obtained at the entrance of the prestripper, the beam is then focused and steered through the machine by observing the faraday-cup current and the beam profile display at the exit of every accelerating cavity or beam line section. A fairly large number of diagnostic elements proved to be extremely valuable.[8] The whole tune-up of the beam, which is done manually so far in the local control areas along the machine, takes about four hours, if no major break downs occur. During this procedure about 600 on-off switches and buttons have to be pushed, 60 range switches have to be set, 340 analog knobs have to be turned, and 55 meters and 15 oscilloscopes have to be observed, clearly a challenge for an automatic control effort.

Thus the present phase of manual control has been considered as an accidental or temporary exception; no control room and no classical console was provided for a convenient manual control of the machine. Actually when tuning the beam, the operators must move in the equipment aisle from control area one to area 5, in the latter the beam transport elements and the beam diagnostic elements of the experimental area can be operated. If every thing goes well, the operators remain there and observe the current signal provided by the experimenters. If the beam disappears, they must go back in the individual local control areas and find out what was going wrong. Fortunately the reasons for a probable break-down are limited to a few well-known sources.

There are two reasons why the originally envisaged computer control from the console in the main control room is not yet in service. One reason was discussed above, set values of many elements proved to be non-reproducible so far, and it is of questionable value to do the tuning to every element manually via a computer system from the main console with a time consuming adressing of the individual elements. The most important reason, however, is the fact that the system programming of the link between the central computer and the five local data aquisition computers was considerably behind schedule for some time, and the hardware interface for few systems still is not available or not operationable presently, thus delaying the activity of writing the actual operation programs. In the meantime the pressure to deliver the beam on the target was such that not enough shifts for program check out could be attributed to the controls group. There are still numerous interferences between different program performances, which can only be discovered in a real beam tune up activity. This situation will be cleared after the present shut-down period and a convenient operating of the machine from the main control room will start at the end of this year.

There is no clear answer to the question, what should have been done differently: The question, whether a decent manual control console should be provided with a later introduction of a computer aid as it was applied to existing accelerators, or whether no manual control should be provided at all, and everything being accessible only by the computer system. The way the Unilac was put into operation was a compromise between both alternatives, with the inherent tendency to improve the manual and local control whenever possible. The argument can be reduced to the vague statement that a simple system, a proton linac for instance, can easily be computerized, while a complex machine, which really merits a computer aid, must undergo a time consuming period of ambivalent philosophy, resulting hopefully in the final success of a perfect computer control system.

In the first 8 months of routine operation of the Unilac the beam intensity was raised steadily. Optimum values are: argon 10^{13} p.p.s., krypton $5 \cdot 10^{11}$ p.p.s., xenon 10^{11} p.p.s., and uranium 10^{10} p.p.s. Fig. 1 shows typical data of beam transmission in the machine.

Only 20 % of the presently submitted proposals for experiments require maximum intensity. For some experiments, beam intensity degraders have been used, reducing the intensity by a factor of 10^4. Due to various deficiencies either of the cavities or in the amplifiers, only 10 to 12 of the 20 single gap cavities have been in use, thus only 75 % of the maximum energy was available. The variation of the output energy was used in about one third of the present experiments. The energy spread was not yet measured precisely and seems to depend strongly on machine tuning. Values of about 1 % seem to be routinely attainable. The debuncher at the end of the machine was not in service so far. The monitoring of the bunch structure of the beam proved to be quite convenient for tune up purpose, and time of flight measurements were used for energy determination.[8]

Beam Transmission of the UNILAC

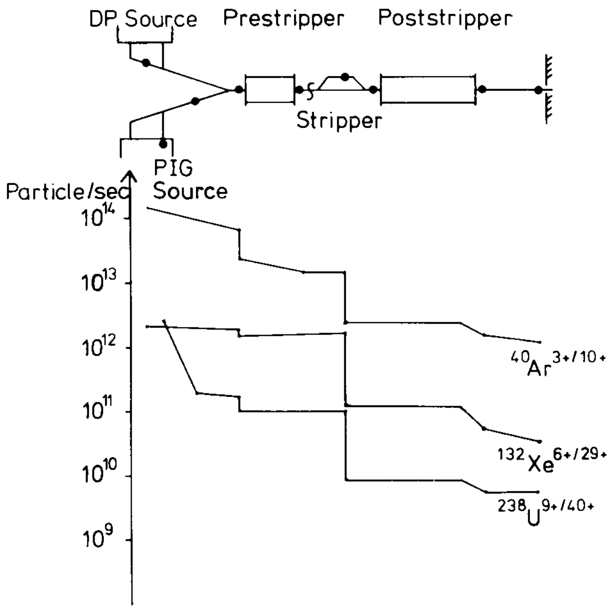

Fig. 1 Typical beam intensity measured in the different linac sections for Ar, Xe and U particles with charge state figures for the prestripper and poststripper. The step functions account for the acceptance of the rf prestripper structure and the charge analysis after the stripper. The slope of the argon curve in the injection line and the prestripper may result from an accidental tune up, where maximum intensity was not required. The slope of the uranium curve in the preinjector line is due to the temporary lack of few quadrupole power supplies. The intensity decrease at the end of the machine is not clear at present.

In the past months, one week per month was preserved for modifications and improvements of the machine, and one additional shift per week for maintenance. Both activities are no more found necessary in future on a scheduled basis. Maintenance and improvements will be done in accidental downtime and during ion source service hours. However, more shifts will be devoted to machine studies and computer control experiments in future.

Future Developments

Actually there are so many details, mentioned before, which have to be brought up to the design status during the next year that no additional and distinct improvement program is envisaged presently. A beam splitter, providing three simultaneous beams in the main experimental area will be installed at the end of this year. Several rebuncher helices are being fabricated for restoring the bunch structure in the target area for timing signals. An rf chopper in the injection beam line is under consideration in order to increase the microstructure sequence for special requirements in time of flight experiments. Finally a modest effort is spent for a synchrotron study, including the Unilac as an injector linac.

Acknowledgement

The author wishes to express his gratitude to Prof. Ch. Schmelzer, to the father of the Unilac project. His vital interest in the design and construction phase of the machine was stimulating for every staff member. His continuous care for comfortable working conditions was the basis for the successful build up period of the whole laboratory.

References

1 Ch. Schmelzer, Study of a Variable Energy Heavy Ion Linear Accelerator. Proceedings of the 1968 Proton Linear Acc. Conference, Brookhaven

2 Ch. Schmelzer and D. Böhne, GSI, A New Heavy Ion Research Facility. Proceedings of the 1970 Proton Linear Acc. Conference, NAL

3 D. Böhne, Status Report on the Unilac Project. Proceedings of the 1972 Proton Linear Acc. Conference, Los Alamos

4 T. Niewodniczanski and E. Malwitz, Mechanical Design Features of the Unilac, Proceedings of the 1972 Proton Linear Acc. Conference, Los Alamos

5 N. Angert et al., The Unilac Injector, these Proceedings

6 K. Kaspar, The Unilac Prestripper Accelerator, these Proceedings

7 N. Angert et al., The Stripper Section of the Unilac

8 J. Glatz et al., Beam Diagnostic System of the Unilac

DISCUSSION

D.A. Swenson, LASL: You mentioned the Alvarez tank was undergoing a cleaning process and soon the surface finish would be back to its original. Would you describe what sort of cleaning process you anticipate?

Böhne: Our standard procedure is alumina powder going through three different grits of alumina powder suspended in distilled water and by this polishing we re-establish the original surface though there have been damages in the cover.

F. Selph, LBL: What are the staffing requirements to run the accelerator, the UNILAC?

Böhne: We have one crew consisting of one shift leader (in most cases that is a staff member) and two operators. And we have about seven crews and in addition say about 12 maintenance people. But we have call on quite a large facility and the accelerator deserves also the highest priority in case something fails so we can have 50 or 100 people.

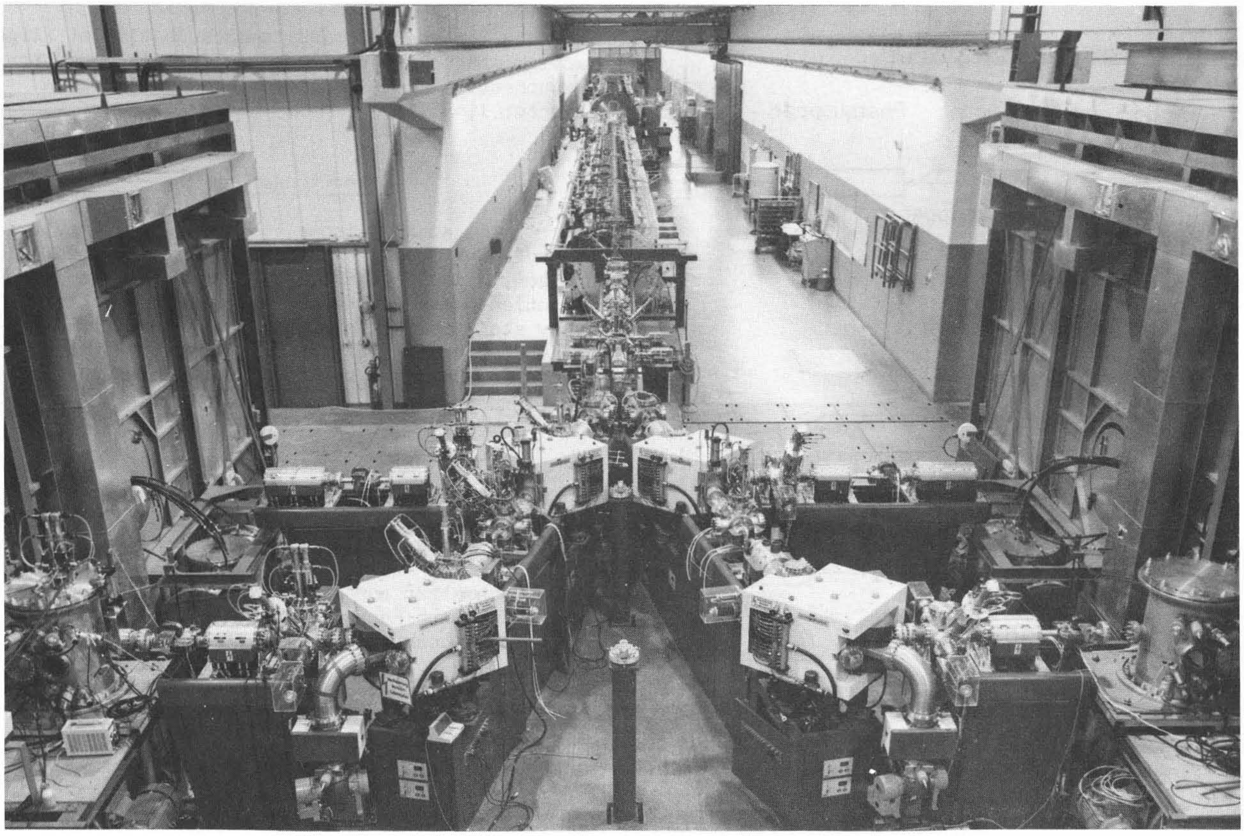

Fig. 2 The injection beam lines and the two injector faraday-rooms during the assembly phase.

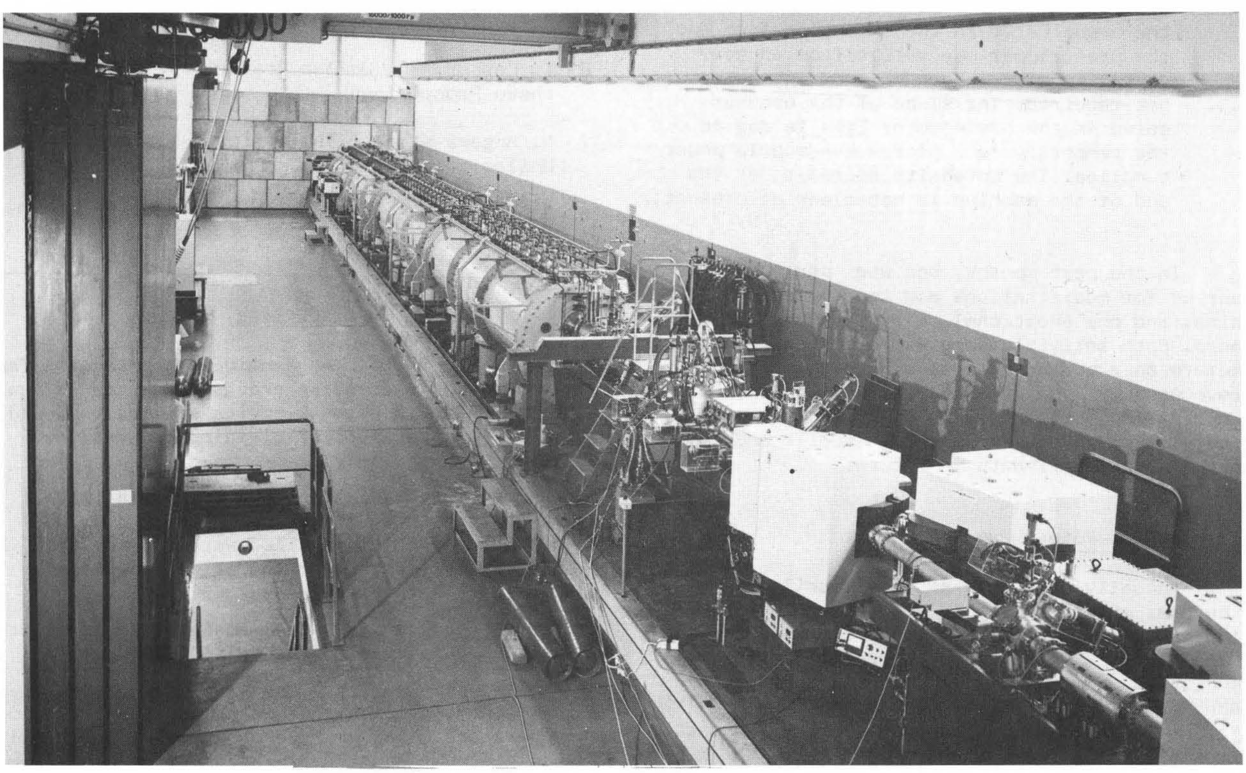

Fig. 3 The prestripper accelerator with the stripper and charge analysis system in the foreground on the right.

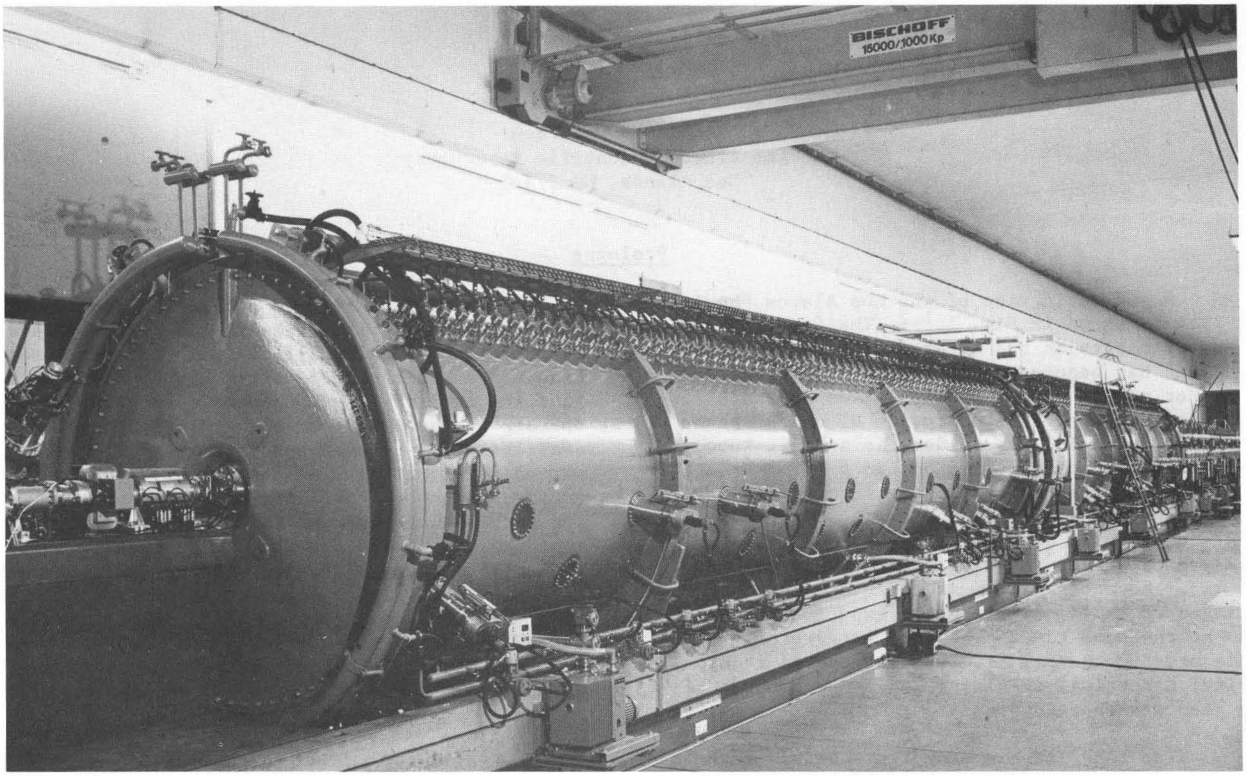

Fig. 4 The Alvarez section of the poststripper.

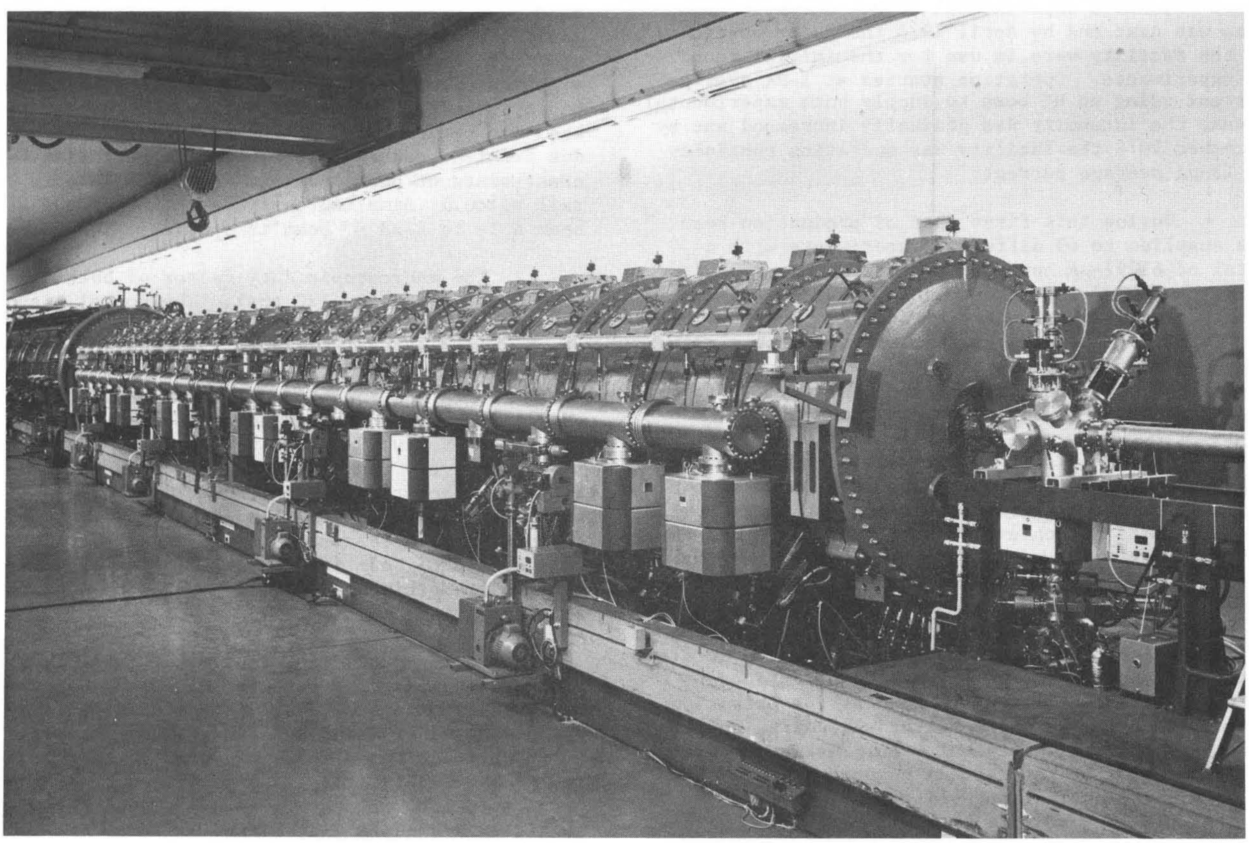

Fig. 5 The single gap cavity structure seen from the end of the poststripper.