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LONGITUDINAL AND TRANSVERSE BEAM OPTIMIZATION AT THE UNILAC

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Summary

The different categories of beam optimization procedures are described, including both longitudinal and transverse phase planes. The description of the transverse computer-aided procedures concentrates on the low energy beam transport system, but these methods are applicable to the whole machine. In case of the longitudinal adjustment, typical procedures for the accelerator subsystems are presented. Present status, operating experiences and future development of the programs are reported.

Introduction

The frequent changes of accelerating conditions typical of a multi-particle, variable energy machine, tend to decrease the overall operational efficiency of the facility. Therefore efficient computer-aided operating procedures become essential.

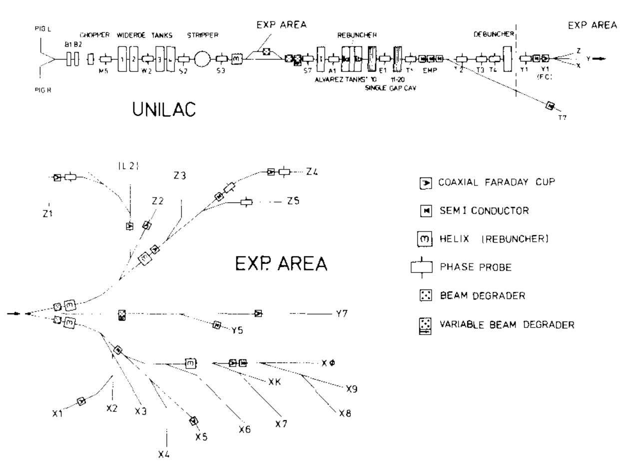


Fig. 1 Schematic diagram of the Unilac

Figure 1 shows a schematic diagram of the Unilac. From operating experience gained during the start-up phase and the subsequent routine operation, the major effort in the development of optimization procedures was focused on the following subjects:

low energy transport system from the ion source to the Wideröe preaccelerator; adjustment of the multi-stage rf accelerating system and its associated pre- and rebunching elements; energy variation by the single-gap resonator chain; high energy beam transport to the experimental areas and matching to the experimental setup; tune-up of time structure for the remote target stations with the rebuncher-debuncher system.

In the final stage, most of the procedures will be effective on-line programs which should contribute much to the accelerator performance. But the development of control programs featuring such advanced control functions requires a thorough understanding of the accelerator behavior. All hardware components have to be stabilized. Shortcomings of the computer system can have a considerable effect upon success. The present status of the Unilac is reported in a companion paper.[1] Discussion of the development of optimization routines will follow.

The extensive beam diagnostic system[2,3] at the Unilac proved to be extremely valuable for the development of operating procedures. In case of the longitudinal beam optimization, the signals of the phase probes, coaxial Faraday cups and semiconductors are mainly used. For the transverse optimization, the emittance measuring apparatus, profile grids and Faraday cups are required. The optimization procedures are based on combined use of these beam measuring devices and different transport computer codes. In the following sections the procedures will be described.

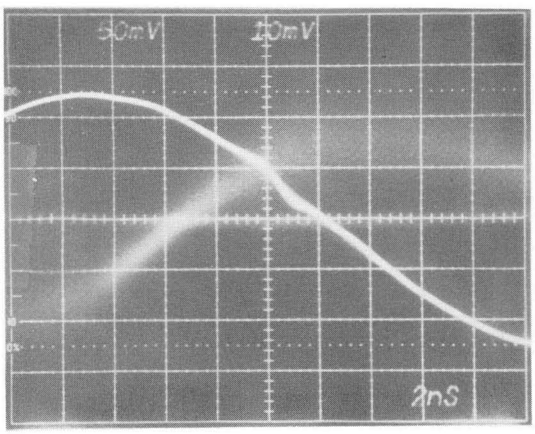
Longitudinal Matching Procedures

Many capacitative phase probes are positioned along the Unilac (Fig. 1) for use in energy measurements, correct setting of the rf amplitude and phase and matching of the different rf substructures. The time-of-flight method for energy measurements was described in detail in 1976[2] and in a separate contributed paper.[3] The advantages of the method are high accuracy and simple handling. The operations crew can quickly adjust and recheck the output energy of each accelerating substructure. The signals of phase probes T1, T2, T3, T4 (see Fig. 1) are now used for a computerized on-line measurement of the energy. The energy is displayed on the main control room console with a high refresh rate. Electronic devices and data processing are also described in Ref. 3.

Longitudinal matching procedures of rf substructures will be described in the following two sections: adjustment of the prebuncher system and matching of the pre- and poststripper accelerator. Up to now these procedures were under manual control; computer control was envisaged but with a low level of priority.

Two buncher cavities at 27 MHz are installed in front of the Wideröe prestripper accelerator.

The beam pulses from the dc preaccelerator have to be matched to the phase acceptance of the Wideröe linac. For correct setting of the rf amplitude and phase of both cavities, the following adjustments must be made: The unbunched beam must be injected in the first Wideröe tank at the injection energy of 11 keV/u. The bunch structure can be measured by the phase probes behind the first tank. Each bunching cavity is powered separately. The rf phase is adjusted to the value at which no displacement of the bunch signal occurs. An indication of the correct phase is the increase of intensity and an improvement of the bunch structure. Now with the correct setting of buncher phases, corresponding to a reference phase of -90°, the amplitudes are optimized for a maximum beam intensity. The structure of the prebunched beam can be measured by the phase probe (M5) in front of the Wideröe tank. Figure 2a shows the time relation between the bunch signal and the rf signal of the first Wideröe tank at the correct settings of the buncher cavities.



M5

Fig. 2a Time relation between the signals from phase probe behind the prebuncher and the rf amplitude of the first Wideröe tank

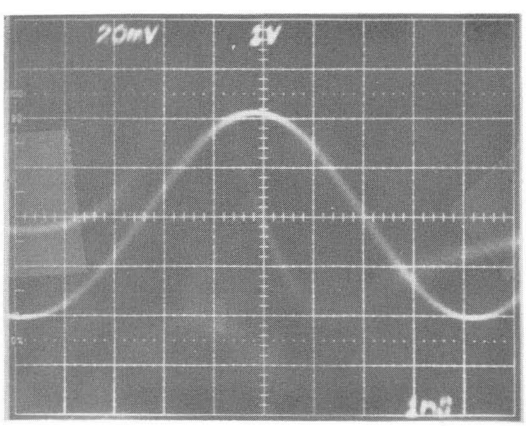


Fig. 2b Bunch position with respect to the rf signal of the first Alvarez cavity

The operators use this display for the adjustment of the injection energy. The sensitivity is quite high; a change of the dc accelerating voltage by 10^{-3} results in a bunch displacement of 1 nsec.

The output energy of the prestripper accelerator can be changed in a range of $\pm 2\%$ without deterioration of the time structure of bunches. In this way it is possible to adjust the design injection energy of the poststripper accelerator. The energy can be measured very accurately by phase probes S7 and A1 (distance 14.4 m, sensitivity for deviation from the design input energy of Alvarez 1 $\Delta W/W$ (%) $\sim 0.23 \cdot (6.6 - \Delta t$ (nsec))). Taking the fixed relation between the rf tank and S7 phase probe signals, the precise rf phase of the first Alvarez tank, determined experimentally, can be adjusted and checked during routine accelerator operation (Fig. 2b).

The change of energy due to the damage of stripping foils at high beam intensities, results in a noticable displacement of the bunch signal. This change influences the beam quality considerably. Measurements are presented in Ref. 3.

With intensities of few μA U^{9+} at the stripping foil, for instance, an energy change occurs after only 1 hour of operation. At present the operator has to check and readjust for correct operation. Mainly for experiments, the efficiency of the machine drops drastically. A project exists for automatic control by a microcomputer based system. The proposed procedure is shown in a program flow-chart (Fig. 3).

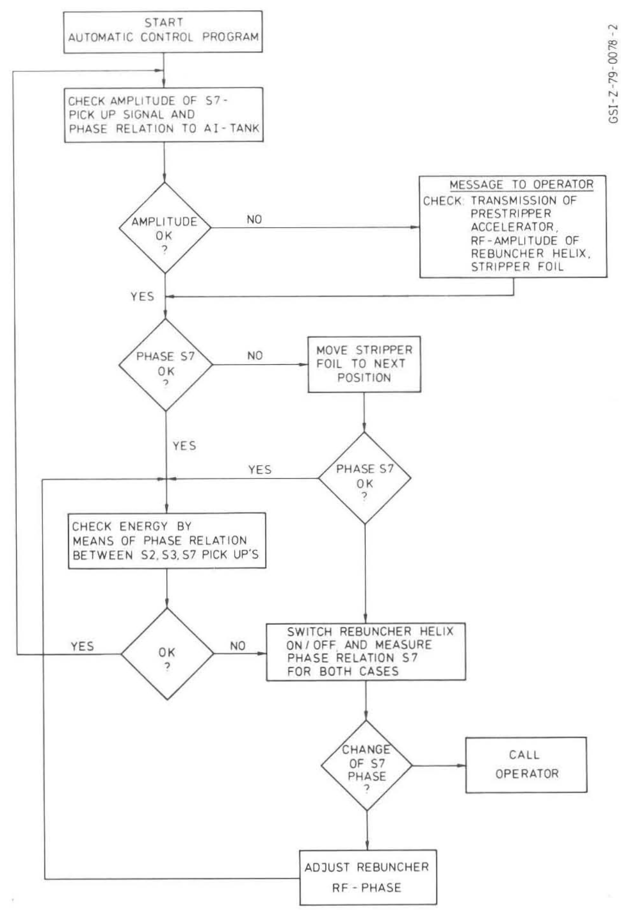


Fig. 3 Schematic diagram of on-line control in stripper section

In the following paragraphs two procedures are described which are largely computer-aided. Since the rf system has not been under computer control, the optimized settings of rf amplitude and phase are manually controlled. The design of a microcomputer based control system for the rf system was started in parallel with changes of the rf hardware and should be ready at the end of 1980.

The final energy of the Unilac can be varied in a broad range by the 20 single-gap cavities; a maximum effective accelerating voltage of about 24 MV can be generated. Energy changes are required often, sometimes 4 - 8 times during an 8-hour shift. Therefore quick adjustment of the cavities to save set-up time is the goal of computerization of the procedure.

The input parameters for the resulting optimization procedure are as follows: mass number and charge state, energy in front of the single-gap cavity chain, rf phase of the last Alvarez tank in operation in relation to the 108-MHz reference line, and the requested final energy. The energy gain of the i-th cavity is given by

$$\Delta W_i = \zeta/A \cdot U^i_{Cal} \cdot U^i_T \cdot T \cdot \cos\phi_s$$

(T Transit-time factor, U^i_T rf probe signal)

The factor U^i_{Cal} is a measure of the peak accelerating voltage ($T=1$, $\phi_s=0$) for the i-th cavity at a probe signal of 1V. These values were experimentally found by measuring the maximum energy gain; they differ among the 20 cavities. All the 20 values are stored in a database. For the computation of power levels and the rf phases, the procedure takes into account the range of possible power levels which are also kept in a database. The agreement between requested and measured energy after setting the calculated values is quite good (1 - 2%). Only manual (or later automatic) fine tuning of the rf amplitude of the last cavity is required afterwards.

Some experiments require a sharp time focus of the bunch on the target, or an improvement of the energy spread. Then a single-gap resonator at the end of the linac and 4 helix resonators are used. At the linac output, the pulse width is 0.6 - 1.5 nsec, depending on the energy and the adjustment of the linac rf structures. Corresponding to an energy spread of 0.1 - 0.3%, the pulse width increases over a drift length of about 80 m to 2 - 5 nsec. The tune-up procedure for an improved time structure is as follows. First, energy spread and bunch width are measured;[3] from that the longitudinal phase ellipse at the end of linac can be calculated. This phase ellipse is transported to the position of the helix resonator (the debuncher is switched off). If the pulse width is within the limit of 70^o (at 108 MHz), the bunch structure is optimized only by the second rebuncher. The rf amplitude is now adjusted for a minimum pulse width on the target position. Depending on the energy spread of the beam after acceleration, the phase width sometimes exceeds the limit of 70^o. In order to avoid non-linear effects of the rf field, a combined action of two resonators provides the optimum transformation. The first is adjusted as a debuncher; the energy spread is now reduced and the pulse width at the rebuncher is small enough for a linear transformation.

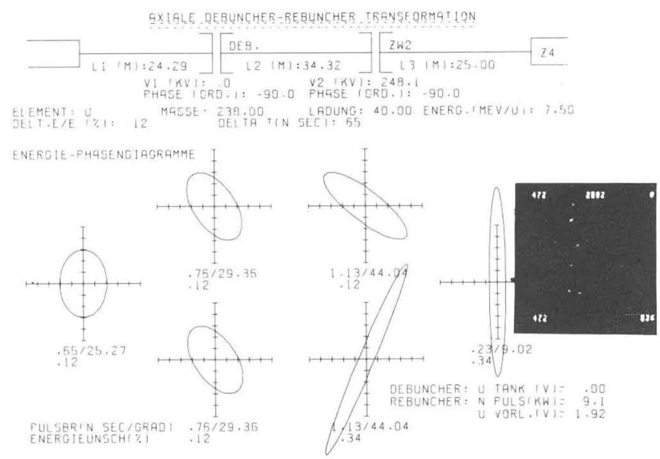


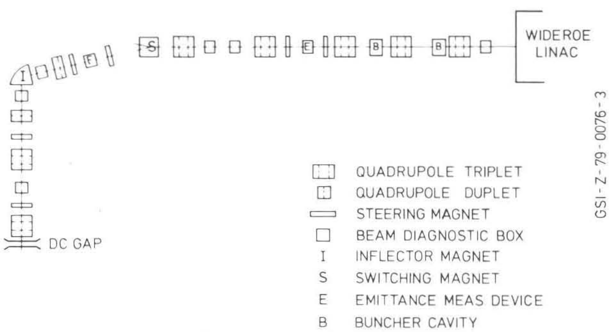
Fig. 4 Output of the program for the rebuncher-debuncher system (right: measured bunch width on the target)

The output of this optimization program includes mainly the following information: Automatic selection of the cavities to be switched on, the rf parameters, and pulse width at target position. After setting of the calculated values, normally fine tuning immediately leads to an optimum width. The measured pulse width is in good agreement with the calculation by the computer program. An example is given in Fig. 4.

Transverse Beam Optimization of the Injection Beam Transport System

Compared to a proton machine, the low energy beam transport system of a multiparticle accelerator is much more complex. The Unilac injector was described in detail in Ref. 4. Figure 5 shows a schematic diagram of the beam line.

The most important properties are summarized. With the two dc-preaccelerators symmetrically arranged with the axis of the Unilac, ions of all stable elements from a Penning source are accelerated to 11.7 keV/u. One single charge state can be selected; the momentum dispersion of the transport line allows for a maximum mass resolution $\Delta m/m \sim 250$. Alternatively, a non-dispersive mode is used if isotope separation is not necessary. The aperture of the beam line and the magnetic lenses is 4 cm. The radial acceptance of the section from gap to the switching magnet allows transport of a beam with the maximum emittance of 32 πmm-mrad. The acceptance from the switching magnet to the input end of the Wideröe accelerator is 130 πmm-mrad. The operating experiences are described in Ref. 1.



LAYOUT OF THE UNILAC LOW ENERGY TRANSPORT SYSTEM

Fig. 5

The computer-aided optimization procedure consists of the following steps. The magnet currents are set from calculated data or data stored from earlier runs. These settings hardly ever result in a sufficient beam transmission and mass separation. The reasons are manifold: non-reproducible emittance for different ion sources, different parameter settings of the ion source for optimum intensities, tolerances of geometrical dimensions, disabled elements, misalignments, etc. If the beam intensity is not sufficient at the position of the emittance measuring device, an improvement has to be reached by retuning of the ion source and the beam matching elements. The measured emittance is transformed to the input of the transport channel with the actual settings of the magnets. Now an optimizing program calculates new settings for an optimum transport.

An important postulate of the described procedure is that the transport system is computable. Therefore time-consuming activities were started to bring all the components to their design values. The effort has mainly included verification of the calibration curves of all magnets, the precise and reproducible reaction of the magnet power supplies to the command signals, the physical locations of magnets and beam diagnostic elements. The success of this work is demonstrated in Fig. 6. The emittances were measured at two positions of the injection beam line (see Fig. 5) and in each case the envelopes were calculated; both envelopes agree very well. For a further check, the profile widths were measured along the beam line; the measurements confirm the calculated envelopes, too. The transformation excludes the section from the ion source to the gap. There were many changes of hardware, focusing elements were replaced, and the gap was reconstructed. This section will be included later into the optimization procedure.

For a successful optimization of beam transport lines, the measurement of the emittance at several positions is advantageous. The installation of more emittance measurement boxes is costly

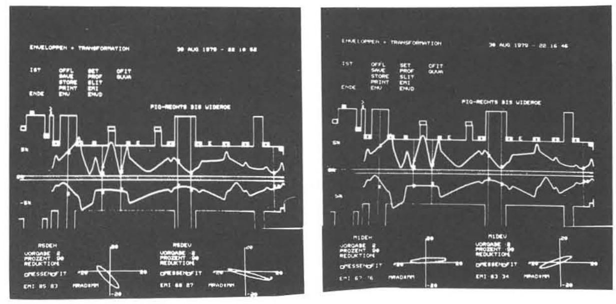


Fig. 6 Calculated envelopes on the basis of emittance measurements (+ measured profile width)

and is excluded by space limitations. Therefore an algorithm was developed using the profile data. There are about 50 profile harps available along the Unilac and in the experimental area. The basic idea is described in Ref. 5; the modified algorithm and the program structure are explained in Ref. 6. The ellipse parameters $\alpha,\beta,\gamma,\varepsilon$ are calculated by measuring the beam width (horizontal and vertical) at 3 different quadrupole settings from the equations

$$a_\nu^2 \beta - 2a_\nu b_\nu \alpha + b_\nu^2 \gamma = \frac{W_\nu^2}{4\varepsilon} \qquad = 1, 2, 3,$$

where a, b, c, d are elements of the 2 x 2 transfer matrix from the quadrupole to the profile grid. Afterwards the emittance ellipse can be transported from the input of the quadrupole to different places on the transport line. Tests of the algorithm have shown that in many cases the measured emittance is determined correctly. Sometimes differences occur in the size of the area, but the inclination is correct. In few cases a solution of the equations does not exist. Stabilization of the routine may be expected with more sophisticated evaluation methods, on which work is underway. The first improvement was achieved by taking the profile parameters at 16 different quadrupole settings. The half widths and full widths are fitted by spline functions. An example is given in Fig. 7. For the evaluation three settings can be selected.

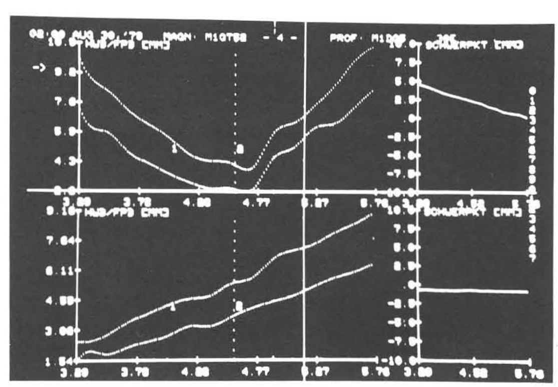
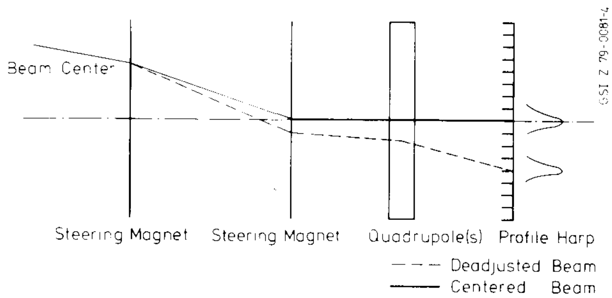


Fig. 7 Display of fitted profile data for the horizontal and vertical plane

In Fig. 7, on the right hand side, the displacement of the beam center at different quadrupole settings is displayed. Since a shifted beam influences the effectiveness of all the transverse optimization procedures, an automatic beam steering program is available. It can be activated at many places in the transport system. A schematic of the steering section is shown in Fig. 8. First, the displacement and slope of the beam center in front of the first steering magnet are determined by measuring the displacement on the profile grid at two quadrupole settings, then, the computer code calculates the set values for the steering magnets.



Layout of the Steering Section

Fig. 8

Organization of the Optimizing Procedures

The optimization procedures are controlled through means of an interactive graphic display. Single routines can be selected. The main routine for transverse optimization starts with an emittance measurement. The program structure is shown in Fig. 9.

The basic idea of the optimization procedure has been described in this paper. The program also contains options which were originally provided for machine development, but they are also a valuable tool for adjustment of the machine during normal operation. One of these options is as follows: After an emittance measurement the envelopes are calculated and displayed. Then, the settings of the quadrupoles can be varied (on- or off-line) and the resulting envelope will be displayed. Furthermore, after selecting beam size constraints, new quadrupole settings are calculated. Both procedures were successfully used for the matching to the target position.

The development of a fully automatic optimization routine is in progress. The fit procedures applied up to now are not always successful. The different emittances at the input of the beam line cannot be matched to the defined reference envelope. The limited acceptance (see Ref. 1) requires tight tolerances for the fit conditions. Therefore, an upgrading program for the injection beam line was started. There is no doubt that in the future the optimization procedure will bring about better results and that the efficiency of the Unilac will increase.

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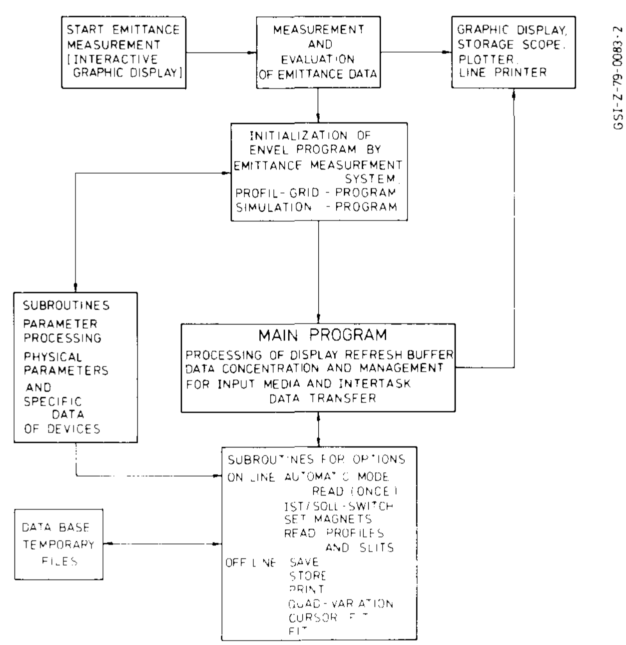

SCHEMATIC DIAGRAM OF THE PROGRAM STRUCTURE FOR TRANSVERSE BEAM OPTIMIZATION

Fig. 9

Discussion

Jaeschke, Heidelberg: What is the energy resolution that you can get with your phase probe detecting device?

Klabunde: In the region of 5×10^{-3}.

Jaeschke: How many of these computerized steering sections that you describe are you now running?

Klabunde: Two in the injection line and two in operation at the high energy end. But, we have many places of this kind of arrangement, but these are the only ones used so far.

Ohnuma, FNAL: What kind of device do you use for your energy emittance measurements?

Klabunde: Just a simple slit-collector system.