

COMPUTER-AIDED TUNING PROCEDURES AT THE UNILAC

L. Dahl

GSI, Gesellschaft für Schwerionenforschung mbH, D-6100 Darmstadt, Fed. Rep. of Germany

Abstract.- Two interactive on-line computer codes for tuning of beam transport elements at the Unilac are described. One is based on an emittance measurement and designed to match the particle beam to a given acceptance of an accelerator subsystem by evaluation of the behaviour of a corresponding computer simulated beam and subsequent automatic transport element setpoint adjustment. The other computer program aligns the beam automatically onto the ion-optical axis at specified positions along the accelerator. Two algorithms for computer controlled steering corrections are presented. Present status, operational experiences and future plans are reported.

1. Introduction.- Operation of a typical variable particle and energy accelerator requires computer-aided operating procedures which enable the reproducible tuning of the transverse properties of the ion beam: for frequent changes in ion-species, energy, target positions of the experiments and beam splitting conditions. In order to preserve maximum transmission occasional retuning is necessary. This has to be done whenever transverse emittance variations occur: changing of the ion source within an experiment run, variations of ion source parameters, time depending influence of the stripper foil or instability of magnet power supplies. Especially the beam splitting system is very sensitive to beam emittance variations.

The successful application of our on-line codes is based on the assumptions that all hardware components are stable and that magnet specifications and all geometrical data of the sections to be matched are exactly known. All data required have to be available to the computer. The extensive beam diagnostic system at the Unilac proved to be extremely valuable for the development of operating procedures, especially emittance measurement devices and profile grids.

Fig. 1 shows a schematic diagram of the Unilac. The emittance measurement devices mark the beginnings of the tuning sections. Beam alignment sections outside the accelerating structures start with a pair of steering magnets and end at a profile grid. The idea is to produce at these locations an aligned beam with defined transverse beam parameters matched as closely as possible to the respective acceptances of the successive accelerator tanks or beam transport lines. Then nominal currents in the quadrupoles of these subsystems should lead to maximum transmission.

In the following a description of the emittance matching code TSO (Transversale Strahl-Optimierung) and the beam alignment code SGL (Strahl Gerade-Legen) is given.

2. Transverse beam emittance matching.- The on-line computer code TSO initiates an emittance measurement and calculates in a computer simulation values for the quadrupoles in a specified transport line in order to match the transverse beam emittance to the respective acceptance¹.

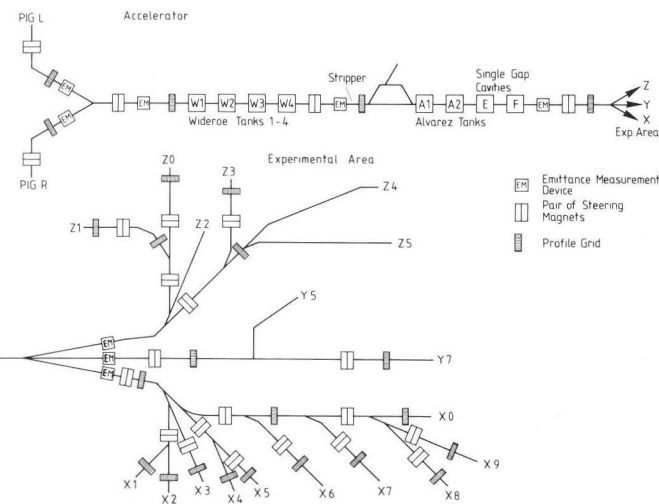


Fig. 1: Schematic diagram of the Unilac.

	NOMINAL		OPTIMIZED
L5QD91	4.69537	L5QD91	6.30903
L5QD92	4.11701	L5QD92	5.45435
M1MU1		M1MU1	
M1QT11	1.69821	M1QT11	2.43256
M1QT12	1.55744	M1QT12	1.90059
M1QT13	1.94395	M1QT13	3.91579
M1QT21	1.68602	M1QT21	1.90032
M1QT22	2.86736	M1QT22	2.64498
M1QT23	3.54710	M1QT23	2.99204

EMD: Emittance Measurement Device

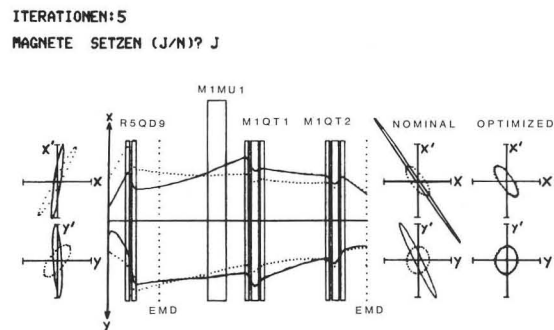


Fig. 2: Computer simulated beam matching.

Fig. 2 shows as an example a tuning section in the injection channel. Reference input-, output-emittance and envelope are indicated by the dotted lines. The real beam emittance is measured with the first measurement device and transformed back to the entrance. This position is identical with the exit of the mass separating system. The advantage of back transformation is the inclusion of the quadrupole doublet R5QD9 into the fitting procedure. Real input emittance and optimized envelope are drawn by solid lines. At the exit of the system first the emittance calculated from design values and second the emittance belonging to the fitted envelope are drawn over the dotted designed output emittance. The Unilac injection line has the advantage of another emittance measurement device at the end of the focusing channel to check the result of the tuning.

The mathematical problem is to minimize the error function of real and reference parameters of the ion beam:

$$F(p) = \sum_{i=1}^m f_i^2(p) = \sum_{i=1}^m (r_i(p) - r_i^s(p))^2 = \min$$

$r_i(p)$ measured beam properties

$r_i^s(p)$ reference beam properties

$p = (p_1, \dots, p_n)$ beam line parameters.

In general the system of equations

$$(p_j - p_j^s) = (A^T \cdot A)^{-1} \cdot A^T \cdot (r_i - r_i^s) \quad (1)$$

has to be solved to match the beam to design values. A is a functional matrix with partial derivatives $\delta f_i / \delta p_k$, $i = 1, \dots, m$ and $k = 1, \dots, n$. Because $f_i(p)$ are complicated transcendent functions, the functional matrix A is approximated by difference quotients $\Delta f_i / \Delta p_k$. That means only an iterative procedure can be used for the solution of the set of equations.

The computer code TSO uses the "conjugate gradient method" (CGM)^{2,3}, to solve the linearized system of equations (1). This algorithm always finds a solution, if one exists, within N iterations. N is the order of the system. The nominal quadrupole values are taken as initial guess which also could be zero. The coefficient matrix A may be arbitrary. Because the areas of emittances are constant over the defined beam matching sections, the number of transverse beam parameters are limited to four. If the system of equations is under-determined, which is the most frequent case, one of several solutions is calculated. In case of overdetermined systems a least-squares-type solution is obtained. Experiences have shown that the number of four to nine quadrupoles is sufficient for optimizing four transverse beam emittance parameters. More beam line variables lead to greater inaccuracy due to matrix inversion operations. All computer calculations are carried out with double precision (64 bit).

Different errors affect the success of the tuning procedure, e.g. limited precision of the emittance measurement, steering effects caused by an off-axis beam, deviations in magnetic field calibrations, inaccuracies of stored data. Error accumulation and propagation are then reasons for disagreement of the real beam properties with the expected computer calculated parameters at the end of the matching section. A post-correction of the transport elements may be necessary⁴.

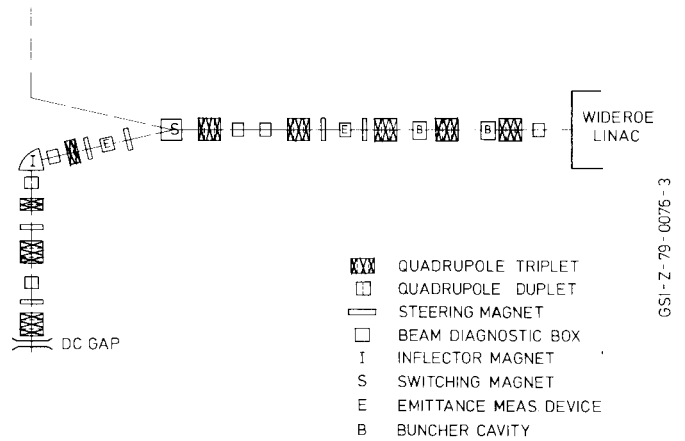


Fig. 3 LAYOUT OF THE UNILAC LOW ENERGY TRANSPORT SYSTEM

Fig. 3 shows the layout of the low energy transport system of the Unilac. The subsystem between the two emittance measurement devices agree with the detailed picture of figure 2. The arrangement allows a post-correction to reduce the matching error in a way described as follows.

The real output emittance will also be measured and transformed back to the entrance of the defined focusing channel. There it is used for input and forms a consistent dataset together with the computer optimized quadrupole values. A second matching of the beam transport line based on this dataset by solving the linear equation (1) for the residual error

$$F^*(p) = \sum_{i=1}^m (r_i^*(p) - r_i^s(p))^2$$

usually results in a significantly reduced difference compared to the first tuning run, otherwise repetition of the post-correction is possible.

In the other beam matching sections only profile grids can be used to test the computer simulated emittance fitting. Advantageous is the large number of grids installed.

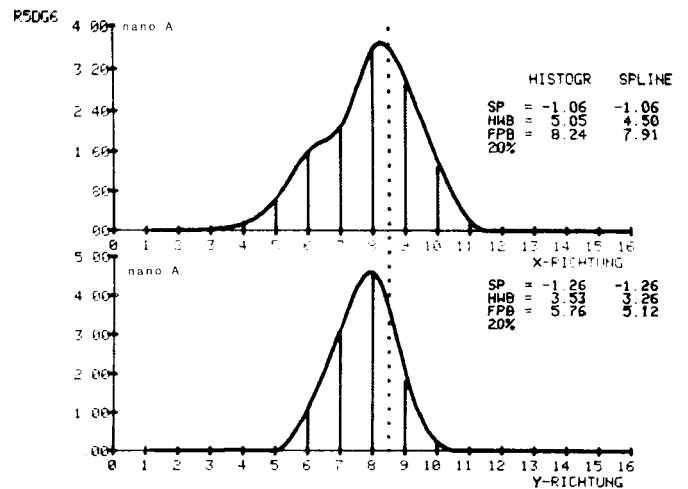


Fig. 4: Profile grid measurement.

The grids consist of sixteen wires 1.5 mm apart in horizontal and vertical plane to analyze the transverse ion beam distributions. These are fitted by spline functions in order to approximate the physically smooth beam profile for better accuracy⁵. The beam width and emittance data are both evaluated from 90 % of beam intensity. If the measured beam profile parameters deviate unpermissibly from the computer calculated envelope, a subsequent treatment can be initiated.

The angles of the optimized envelope to the accelerator axis are considered correct at the position of the profile grid. The vector of the residual error $F^*(p)$ only contains the differences in beam width between measured and computer simulated beam envelope, the errors in angle are set to zero. Comparable to the procedure applied in the injection channel, measured beam width and originally calculated angles of the envelope at the profile grid are transformed back to the beginning of the tuning section. The remaining post-correction is carried out as before. Drastically reduced differences between nominal and real beam width are the result. Differing from the procedure used in the injection channel the beam profile fit is repeated step by step for each grid.

3. Beam alignment methods.- The computer program SGL was designed to align the beam onto the ion-optical axis of the Unilac. This is a basic requirement for the application of beam matching codes, since a shifted beam disturbs the transverse optimization procedures. Two complex algorithms for beam alignment are described.

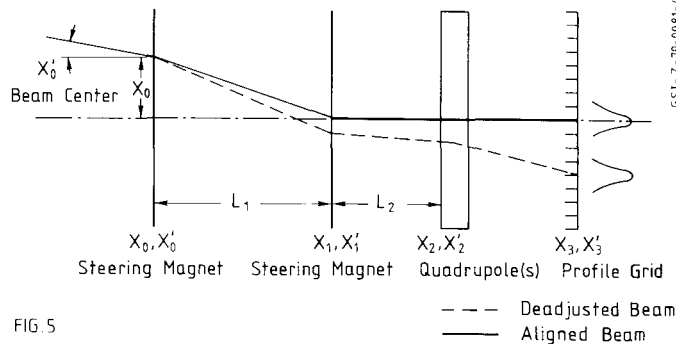


FIG.5

Layout of an Alignment Section with one Profile Grid

In figure 5 the beam line arrangement for a procedure using only one profile grid is drawn. The goal is to determine displacement x_0 and slope x_0' of the beam center at the beginning of the section by measuring the beam center on a profile grid at different quadrupole settings. According to the result a pair of steering magnets at the entrance of the defined beam transport line are adjusted so that the beam crosses the center of the second steering magnet which bends it on the accelerator axis.

Determination of the beam center by profile grid measurements is based on the same spline function fit as shown in fig. 4. The beam center is determined as the center of gravity under the fitted function. To calculate the beam center position x_0 and slope x_0' at the entrance of the first steering magnet, two different quadrupole settings and profile measurements ($n=1,2$) are sufficient by theory.

The transformation

$$\begin{pmatrix} x_3^{(n)} \\ x_3'^{(n)} \end{pmatrix} = \begin{pmatrix} a_{11}^{(n)} & a_{12}^{(n)} \\ a_{21}^{(n)} & a_{22}^{(n)} \end{pmatrix} \begin{pmatrix} x_2 \\ x_2' \end{pmatrix}$$

describes the transport of the beam center as a single particle transformation from the first quadrupole (x_2, x_2') to the profile grid (x_3, x_3'). From this follows a relation for the coordinates of the beam center at the beginning of the first quadrupole:

$$x_2 = (x_3^{(1)} a_{12}^{(2)} - x_3^{(2)} a_{12}^{(1)}) / Z$$

$$x_2' = (x_3^{(2)} a_{21}^{(1)} - x_3^{(1)} a_{21}^{(2)}) / Z$$

where $Z = a_{11}^{(2)} a_{12}^{(1)} - a_{11}^{(1)} a_{12}^{(2)}$

The constants k_i and currents I_i of the steering magnets are known. The products $k_i I_i$ describe the changes in radial momentum induced by the dipole magnets. This enables to transform x_2, x_2' back to the entrance of the system:

$$x_0 = x_2 - x_2' (L_1 + L_2) + k_2 I_2 L_1$$

$$x_0' = x_2' - k_1 I_1 - k_2 I_2$$

With the condition $x_1 = 0$ the current of the first steering magnet can be determined:

$$x_1 = x_0 + L_1 x_0' + k_1 I_1 L_1 \stackrel{!}{=} 0$$

Hence

$$I_1 = - \frac{x_0 + L_1 x_0'}{k_1 L_1}$$

The remaining radial momentum of the beam $x_0' = -x_0/L_1$ is compensated by the second steering magnet:

$$I_2 = x_0 / k_2 L_1$$

Experiences at the Unilac have shown that accumulation and propagation of errors affect the reliability of the results in case of only two quadrupole variations and profile measurements. Therefore a statistical method has been developed.

Depending on the number of quadrupoles in an alignment section up to ten quadrupole setting variations ($n=1, \dots, 10$) are executed and analyzed with the least-squares-method. By this method the sum of the square deviations Q has to be minimized:

$$Q = \sum (x_3^{(n)} - x_{3s}^{(n)})^2 \stackrel{!}{=} \min$$

$x_3^{(n)}$ measured beam center

$x_{3s}^{(n)}$ reference beam center.

Considering equation (2) and determining the partial derivatives $\partial Q / \partial x_2$ and $\partial Q / \partial x_2'$ displacement x_2 and slope x_2' can be calculated:

$$x_2 = (\sum x_3^{(n)} a_{11}^{(n)} \sum a_{12}^{(n)2} - \sum a_{11}^{(n)} a_{12}^{(n)} \sum x_3^{(n)} a_{12}^{(n)}) / D$$

$$x_2' = (\sum a_{11}^{(n)2} \sum x_3^{(n)} a_{12}^{(n)} - \sum x_3^{(n)} a_{11}^{(n)} \sum a_{11}^{(n)} a_{12}^{(n)}) / D$$

where $D = \sum a_{11}^{(n)2} \sum a_{12}^{(n)2} - (\sum a_{11}^{(n)} a_{12}^{(n)})^2 \neq 0$.

Adjustment of the steering magnets is carried out as described above. Horizontal and vertical plane are treated simultaneously.

Another option to align the beam onto the ion-optical axis of the accelerator is based on a more empirical method⁶. Necessary are a pair of steering magnets followed by two profile grids. Quadrupoles may be located anywhere in this arrangement.

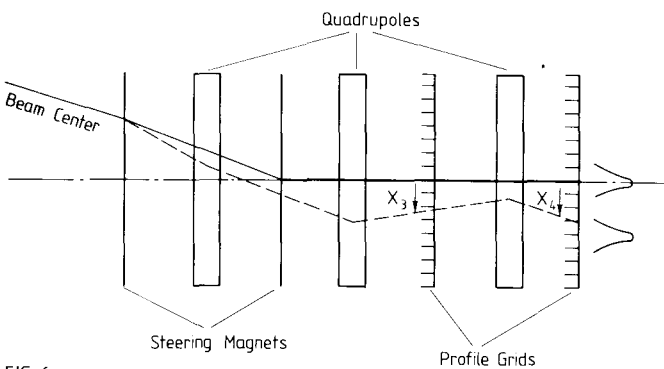


FIG. 6
Layout of an Alignment Section with two Profile Grids

The following linear system of equations describes the steering magnet effects on transverse beam center displacements at the two profile grids including also the effect of the quadrupoles.

$$\begin{pmatrix} \frac{\partial x_3^{(1)}}{\partial I_1} & 0 & 0 & 0 \\ 0 & \frac{\partial x_4^{(1)}}{\partial I_1} & 0 & 0 \\ 0 & 0 & \frac{\partial x_3^{(2)}}{\partial I_2} & 0 \\ 0 & 0 & 0 & \frac{\partial x_4^{(2)}}{\partial I_2} \end{pmatrix} \begin{pmatrix} dI_1 \\ dI_1 \\ dI_2 \\ dI_2 \end{pmatrix} = \begin{pmatrix} dx_3^{(1)} \\ dx_4^{(1)} \\ dx_3^{(2)} \\ dx_4^{(2)} \end{pmatrix}$$

dI_n ($n=1,2$) variations of the steering magnet currents

$dx_m^{(n)}$ beam center displacements at the profile grids m caused by steering magnets n .

The partial derivatives are approximated by difference quotients. These are measured by varying of the steering magnet currents and simultaneous observation of the beam profile centers at the two grids. In order to compensate the deviations x_3 and x_4 of the beam center from the ion-optical axis at the two grids the composed effects of both steering magnets have to be considered:

$$x_3 = x_3^{(1)} + x_3^{(2)} = \Delta I_1^* \frac{\Delta x_3^{(1)}}{\Delta I_1} + \Delta I_2^* \frac{\Delta x_3^{(2)}}{\Delta I_2}$$

$$x_4 = x_4^{(1)} + x_4^{(2)} = \Delta I_1^* \frac{\Delta x_4^{(1)}}{\Delta I_1} + \Delta I_2^* \frac{\Delta x_4^{(2)}}{\Delta I_2}$$

The difference quotients constitute coefficient matrix elements a_{ij} ($i=j=1,2$). From the two equations the modification ΔI_1^* and ΔI_2^* of the actual steering magnet settings necessary to produce an aligned beam can be found:

$$\Delta I_1^* = (x_3 - x_4 \frac{a_{12}}{a_{22}}) / Z_1$$

$$\Delta I_2^* = (x_4 - x_3 \frac{a_{21}}{a_{11}}) / Z_2$$

where $Z_1 = (a_{11} - \frac{a_{12} a_{21}}{a_{22}}) \neq 0$

and $Z_2 = (a_{22} - \frac{a_{12} a_{21}}{a_{11}}) \neq 0$

The angles x_3' and x_4' of the beam center at the profile grids automatically are zero, unless the transfer matrix between the two grids satisfies a special symmetry condition. This alignment method has the advantage that quadrupoles can be positioned anywhere. Like in case of the alignment algorithm first described it seems to be advantageous with respect to the reliability of this option to use a statistical method.

4. Operational experiences and future development.-

Both computer codes TSO and SGL are developed as mainly automatic computer controlled algorithms.

TSO is initiated directly after a computer controlled emittance measurement. For visual control of the matching procedure designed and optimized envelopes with corresponding magnet values are plotted on an interactive graphic display. The operator decides on a further treatment or setting the calculated setpoints. The procedure takes about five minutes including emittance measurements.

For application of SGL a manual coarse tuning of the steering magnets is necessary to produce the beam profile on a grid. The automatic computer controlled alignment procedure is started by pressing the button related to the accelerator section to be adjusted. Typical times for alignment are between two and four minutes, depending on the number of quadrupoles involved.

Both computer codes TSO and SGL have been successfully tested and are often used in the low energy transport line and at the high energy end of the Unilac. Beam matching and alignment of the injected emittance to the Widerøe acceptance leads to maximum transmission up to the stripper. The simply applicable programs and very good reliability of the methods improve the efficiency of the Unilac tuning procedure and unburden operators from manual knob rotating of transport element currents.

Future developments will concentrate on further applications of the described computer aided operating algorithms on different sections along the Unilac.

A new emittance measurement device will be installed directly behind the ion source and will allow to adjust the beam from the high voltage terminal to the mass separator system in an achromatic or dispersive mode.

Another emittance measurement device in the stripper part will permit to match the transverse beam parameters to the post stripper accelerator acceptance. The beam splitting system at the high energy end demands different options for emittance matching depending on the number and positions of experiments running simultaneously. Finally emittance measurement devices in each of the three primary experiment beam lines give the possibility to match the beam achromatically or dispersively to experiment conditions.

Time depending variations of the transverse beam emittance will be continuously monitored by a non-destructive on-line emittance measurement device⁷ which will be installed in the injection channel during the upgrading phase in 1981.⁸ In case of unpermissible deviations the operator will start a retuning to restore the originally adjusted beam emittance.

Beam alignment algorithms also will be applied to other subsystems along the Unilac. The first algorithm described above is well suited for transport lines and will be adapted for many sections in the intertank and experimental area beam lines, especially for steering corrections on target. The second algorithm is better suited for alignment through accelerator tanks because of the arbitrary arrangement of quadrupoles.

The future task is the thorough control of all Unilac transport elements by computer controlled optimization procedures in order to increase the efficiency of the Unilac operation.

5. References.-

- ¹L. Dahl et al., "Longitudinal and Transverse Beam Optimization at the Unilac", Proceedings of the 1979 Linear Accelerator Conference, Montauk, BNL 51134.
- ²M.J.D. Powell, The Computer Journal, Vol. 7 (1964).
- ³A. Zeidler, "Fortran-Subroutine zur Lösung linearer Gleichungssysteme mit Hilfe der Methode konjugierter Gradienten", GSI Arbeitsnotiz 201180 (1980).
- ⁴W. Kneis, "Rechnergesteuerte Strahldiagnostik und Strahloptimierung am Karlsruher Isochronzyklotron", Kernforschungszentrum Karlsruhe, KfK 2835 (1979).
- ⁵V. Schaa, Diploma Thesis, Technische Hochschule Darmstadt (1978).
- ⁶B. Franzcak, "Einstellung von Steerern", GSI Arbeitsnotiz 220776 (1976).
- ⁷P. Strehl et al., "A New Emittance Measuring Device of the Unilac", 1981 Particle Accelerator Conference, IEEE NS-28.
- ⁸P. Strehl, "Beam Diagnostic Devices for a Wide Range of Currents", these proceedings.