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LINAC 2 PERFORMANCE OPTIMIZATION

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Abstract

In recent years the CERN proton linear accelerator Linac 2 operated with an approximately 90% particle transmission efficiency. The losses concerned mainly the first accelerating tank of the equipment. An intelligent procedure that optimizes the operational control settings has been developed in order to eliminate some of these losses and increase the transmission rate. Both on-line and simulation versions of the program are available. This report describes the method of optimization, presents the measurement and simulation results along with the achieved ~3% improvement, points out the limitations which cause the remaining and currently unavoidable particle loss. In the appendix a user's guide of the program is provided.

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1. Introduction

Since 1993 when its high intensity pre-injector line was installed the CERN proton linear accelerator Linac 2 has worked with a beam current of about 150 mA at the end of the equipment [1]. The operational conditions were set-up by beam dynamics simulations and empirical optimizations, which lead to a ~87% particle transmission rate in the linac by that time [2]. Later it was, in several steps, re-optimized up to the recent ~90%. However, this was still lower than simulations had predicted (95%). Measurement showed that most of the losses (~8%) occurred in Tank 1 out of the three linac tanks.

With respect to the forthcoming Large Hadron Collider (LHC) experiment, as well, for which Linac 2 has to provide a proton beam of about 200 mA, there was an interest for a procedure that is able to automatically, through several iterations, set-up the optimal operational conditions. The recent development presented in this report has realized this aim.

The second section describes the method that fulfills the requirements mentioned above providing an on-line process control and a simulation application. The third section presents all the relevant measurement and simulation results together with the improvements achieved. The following section deals with the obstacles of further improvements found during the measurements. Finally a conclusion is drawn.

The on-line program version is L2OPTIM while the simulation version is distinguished by the term L2OPSIM. A description of their usage is provided in Appendix A. In Appendix B TRACE 3-D [3] simulation drawings visualize the major optimization steps.

2. The method

The operation of Linac 2 depends on a large number of control parameters such as power supply amplitudes of the accelerating field and the focusing defocusing quadrupoles in the tanks [1]. In order to perform optimization, especially for Tank 1, in the sense of transmission rate and at the same time to keep the phase-space parameters of the accelerated particles on the same level, the optimization procedure is required on one hand to cope with large sets of variable control parameters and on the other hand to get results in a reasonable time. These criteria were a bottleneck in previous optimization attempts because the processing time increased rapidly with the number of variable parameters.

The present conception combines beam line measurements and equipment control operations with a sophisticated analysis tool. The latter is a CERN supported function minimization program-package often used in physics analyses. Because a user friendly easy-to-use linac equipment access program facility did not exist in the division it had to be developed. For simulation of Linac 2 there are several programs available. For the optimization version a frequently used one has been selected and adjusted to the external conditions.

The method has been implemented in Fortran because the different packages are available in this programming language and it allows for a common development environment. The subsections below provide an overview of the details.

2.1 Program structure

Both the on-line and the simulation versions are composed of three logical elements in a modular way. The program hierarchy follows the scheme of Fig. 1 indicating the different functionalities and the names of the modules associated with them (the two versions are separated by the symbol /). The subprograms shown in the boxes are independent and communicate only with the main module that controls the whole optimization process.

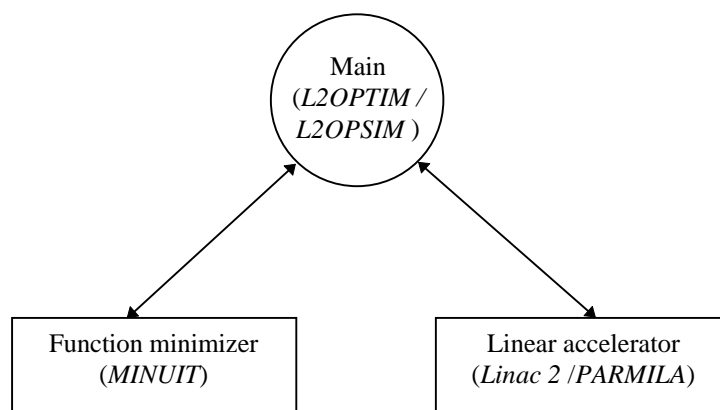


Fig. 1 Block diagram of the optimization program structure

In the structure *Linac 2* and *PARMILA* play roles of the on-line process control tool and the alternative simulation, respectively. They provide the main program with the new beam parameters from which a function value is composed and passed to the function minimizer for analysis. After analysis it returns new control parameter values for the linac subprogram via the central module. The process repeats in the same way until the performance does not improve within a predefined limit.

2.2 Program modules

According to the conception drawn above here follows a description list of the modules:

- L2OPTIM / L2OPSIM

This is the main program module that combines the subprograms together and organizes the data flow between them. It also creates the output files that contain the lists of all the beam measurement and equipment control values. In addition, the on-line version displays the transmission rate in a graphics window step by step. This visualization performs graphics calls through HIGZ, a high level graphics interface module of the CERNLIB library [4].

- **MINUIT**
This is a function minimization program package implemented, tested and installed in the framework of this optimization application both on PC and PS Unix platforms. The source files of the package entirely written in Fortran are available from the CERN Program Library [5]. It is typically suitable for optimization purposes. It finds the minimum value of a multiparameter function and analyzes the shape of the function around the minimum. The maximum number of the variable parameters can be 50 at a time. The application program is requested to provide the minimizer with initial function parameter values and with an initial function value. It is also requested to provide a response function value for each modification of the parameters (see examples in Appendix A).
- **Linac 2**
The control elements of Linac 2 and the measured beam parameters are accessed via PSTOOL, a High Level Interface to CERN/PS Accelerator Control System, which was specially developed in the framework of this application and is now available from the PS Program Library [6, 8]. It provides some simple Fortran callable high level interface routines for basic accelerator control operations via the existing PS Equipment Access (EQP) and Pulse To Pulse Modulation (PPM) library routines that were written in C and C++ program languages.
- **PARMILA**
This is a particle tracking program for linac and transfer line simulations [7]. Here it is used for simulation of Linac 2 and the MEBT (Medium Energy Beam Transport) in front of it. Previously this program was used to help set-up the initial Linac 2 equipment operating control values [1, 2]. It runs relatively fast and is suitable to link to other programs. In order to allow data communication with the main module the original program code was slightly modified.

2.3 Control parameters

The control parameters regulate the operation of the equipment in the PS complex. In this application they are accessed by PSTOOL routines via the PS Accelerator Control System. For the optimization only those ones were used whose values were expected to affect the performance of the linac. According to the program intentions to increase the number of transmitted particles in the linac, the following types of variable control parameters were selected:

- **MEBT**
In the transfer line in front of Linac 2 there are 4 quadrupoles and 2 buncher cavities each of which has a power supply amplitude [1, 8]. Each buncher has a further control parameter, the relative radio frequency (RF) phase, as well. The number of independent variables are: $4 + 2 + 2$, accordingly.
- **Linac 2**
In Linac 2 there are a series of focusing defocusing quadrupoles. Some of their power supply amplitudes are coupled. The number of independent variable amplitudes are: 35, 19, 12 for Tank 1, Tank 2 and Tank 3, respectively [1, 8].

In each tank there are further 2 control parameters: the RF accelerating field amplitude and phase. These are additional $2 + 2 + 2$ independent variables.

2.4 Beam parameters

These are the parameters the optimization procedure attempts to improve in the sense defined below. They are obtained by beam transformer acquisitions in the linac through PSTOOL calls [1, 8]. In each turn the program calculates a function value from the measured beam parameters for the function minimizer. After analysis the minimizer generates new equipment control parameter values that are expected to cause improvements. The beam parameter types chosen for the optimization follow:

- Input beam
The input beam current is measured at the end of the MEBT in front of Linac 2. The linac output strongly depends on it. It is one of the parameters to increase.
- Transmission
There are 2 positions in the linac to measure beam intensities: after Tank 1 and Tank 3. The beam transmissions are by definition the ratios of the input beam at the entrance of Linac 2 and the output beams at the ends of the two tanks, respectively. Hence, the number of transmission rates to increase are 2.
- Emittance
At each plane mentioned above 2 transverse and 1 longitudinal emittance values are measured. The number of emittances to keep low enough before Tank 1, after Tank 1 and after Tank 3 are $3 + 3 + 3$.

2.5 Implementation

The current version does not yet optimize on the emittances. Furthermore, it optimizes only for Tank 1 because most of the losses occur in that one. The function value for the function minimizer is calculated by taking the reciprocal value of the particle transmission rate in this tank.

The on-line program has been implemented on the PS platform IBM AIX/6000 Unix station whilst the simulation one is on Personal Computer. Both have been placed in the corresponding PS program libraries. A complete guide of the usage can be found in Appendix A.

3. Results

The optimization measurements were performed during July, September and October 1996 in three major stages. Each stage took several days due to the shortage of available free beam cycles and the large number of the iteration steps for each control parameter sets. The first measurements were taken exclusively by changing the radio frequency control parameters both in the MEBT and in the linac. Afterwards the

power supply amplitudes of different subsets of quadrupoles were modulated exclusively in the linac or in the MEBT. This stage has resulted in a few percent performance improvement. Finally the different control parameter sets were combined which has not resulted in better configuration but has revealed the problem for further improvements.

For each measurement a dedicated PLS user line MEAPSB was selected to set-up the same initial equipment conditions [8]. During a usual 12 second long supercycle each beam cycle took 1 second. The number of available cycles was usually 1-4 in a supercycle.

3.1 Linac 2

3.1.1 Input beam stability

Before the optimization input beam-intensity measurements were taken in front of Linac 2 to study the time stability. Fig. 2 shows a typical beam behavior after the RFQ (no losses are assumed in the MEBT [1]). The acceptable stability was achieved by averaging the intensities over 10 consecutive beam cycles of the same type. The observable nominal ± 0.5 mA deviation corresponds to $\pm 0.3\%$ fluctuation. That allows to detect systematic changes in the measured beam current from about 0.5%.

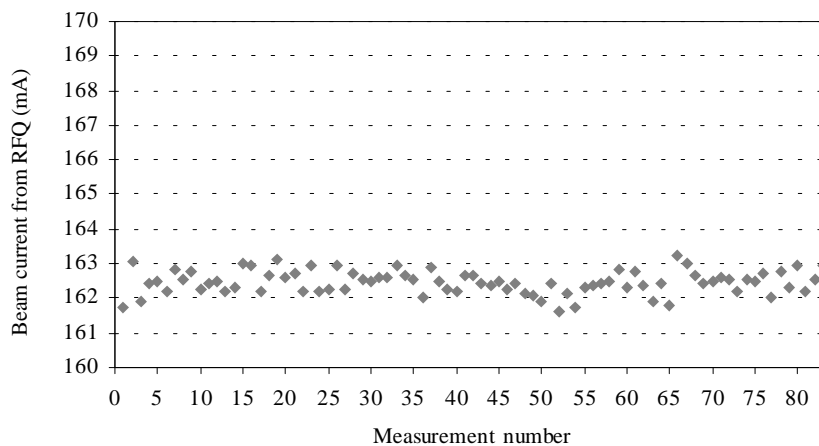


Fig. 2 Typical beam current averaged over 10 cycles at the entrance of Linac 2 before optimization.

3.1.2 Changing radio frequency parameters

These optimization measurements have modified the radio frequency control parameters, i.e. the electric field amplitudes and phases in the MEBT bunchers and in the linac Tank 1. For comparison, corresponding reference measurement data were available provided by an earlier unofficial on-line program called OPTIM.

No relevant improvement was achieved with these parameters compared to the initial state, which confirms the results obtained by OPTIM. Slight increase ($\sim 0.5\%$) could have been achieved for the transmission rate of Tank 1 when the electric field was

allowed to be much higher (about 10 %) than its design value but this is beyond the tolerable limit, in addition.

3.1.3 Changing quadrupole parameters

These optimization measurements have controlled different sets of quadrupoles in Tank 1 and in the MEBT respectively. The number of quadrupoles of one set ranged usually from 4 to 12. All the Tank 1 parameter configurations failed to improve the transmission. In these cases the usual deviation allowed for the parameters did not exceed 10% and only in a few cases were about 15%. Fig. 3 shows the steps of the successful optimization process that modulated only the four MEBT quadrupole power supply amplitudes. In Appendix A the example input file L2OPTIM.IN lists the initial parameter conditions whilst the output files show all the measured beam currents and the corresponding control parameter values.

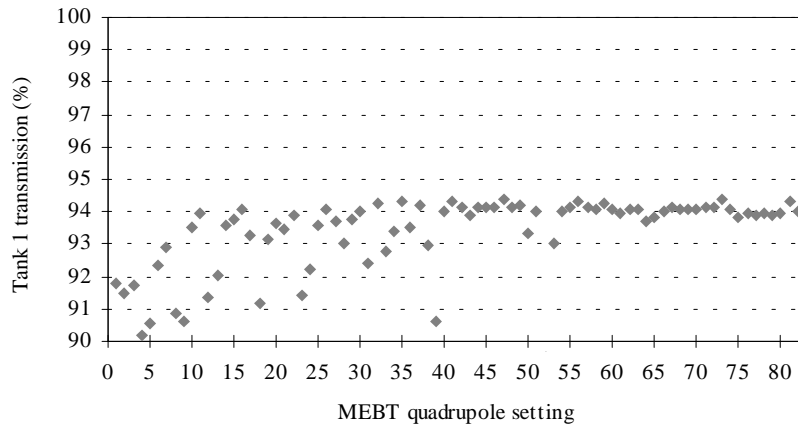


Fig. 3 Transmission optimization in Tank 1 by modulating the four MEBT quadrupoles.

The final beam current values are listed in Table 1. According to the figures 3 types of improvements can be observed: one in the MEBT, one in Tank 1 and as a composite value of them one at the end of the linac.

Measurement position	Beam current (mA)	
	Old	New
entrance of Linac 2	162.2	164.4
end of Tank1	148.8	154.3
end of Linac2	146.8	152.0

Table 1 Measured beam currents before and after optimization

The calculated ratio of the old and new beam transmissions at the end of the linac reflects about 3.5% improvement. With respect to the empirical $\pm 0.3\%$ beam current fluctuation the factor of improvement is better than 3% at the end of Linac 2. In Tank 1 the transmission ratio has increased from about 92% to about 94%.

After the measurements above the optimized control parameters became the new standard settings in the PS complex. In the third stage the control parameters (RF, MEBT, linac) were combined but no further improvement was achieved. However, an additional MEBT quadrupole optimization resulted in a 99% transmission rate in Tank 1 but with a strong drop in the input beam current before the linac (from about 160 mA to about 145 mA). The 3rd drawing in Appendix B shows the corresponding set-up parameters and the simulated beam envelope. The discussion section analyses this case and gives explanations for the encountered problems.

3.2 Simulations

In Appendix B TRACE 3-D simulations show the beam characteristics in the MEBT for the major optimization stages. They are in agreement with those obtained by the optimization simulation program. The first drawing indicates the earlier seen and by L2OPSIM confirmed slight inconsistency (~10% loss in the MEBT and ~5% higher linac efficiency) with the measurements. Therefore the simulations resulted in such optimized control parameters that were not confirmed in Linac 2.

However, the results depend on the initial conditions supplied for the simulations. The currently valid standard input beam parameters are visible on the drawings. With slightly different phase space parameters better agreements could have been achieved (~2-3% instead of ~5%). This reflects a possible reason for the inconsistency. However, the differences were not substantially big, therefore the simulation results were suitable to study the beam transmission effects in the MEBT and in the linac.

4. Discussion

Drawing 3 in Appendix B shows the simulation with the set-up when the transmission rate in Tank 1 was ~99% but the input current dropped. With Fig. 4 it highlights the parts of MEBT where the losses take place. It seems that because the beam expands in front of quadrupole 3 the space is not enough to match the linac without losses.

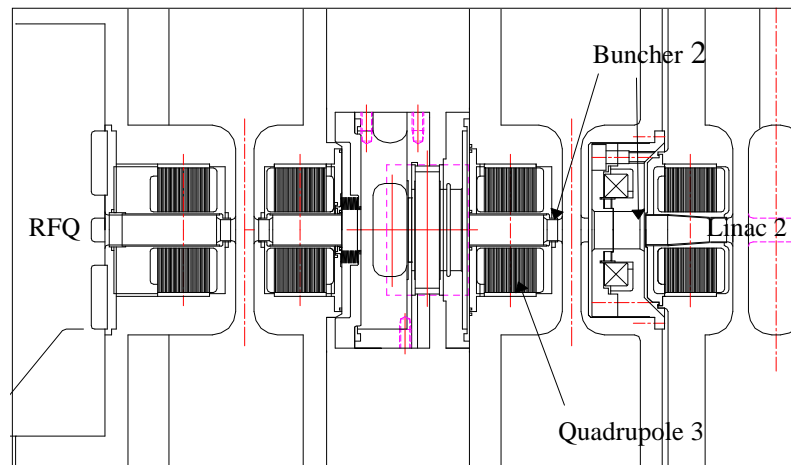


Fig. 4 Schematic drawing of MEBT with the major composing elements

The above effect is strong and is present both in the simulations and in the on-line measurements (~20 % and ~10% extra losses occur in the MEFT, respectively).

A possible way to eliminate the problem is to replace the critical elements indicated on the drawings with elements having wider apertures. From simulations, like the 3rd one in Appendix B, it follows that the minimal aperture size of a new quadrupole in place of quadrupole 3 should be at least 40 mm (instead of the current 25.0 mm). Moreover, the diameter of the first nose of buncher 2 should be more than 36.0 mm (instead of the current 20.0 mm). As a consequence of the bigger apertures, the new elements must work with higher peak fields but this requirement is achievable because currently these fields are only ~70% of the maximum allowed.

5. Conclusion

The program for Linac 2 performance optimization has performed successfully. The final goals have been achieved, the transmission has been increased to the highest level currently possible. The new parameters have become the current standard settings of the PS Accelerator Control System. The linac now produces about 3% (5 mA) more protons than before. The bottleneck of further improvements has been identified and a possible solution for the encountered problem has been schemed up.

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APPENDIX A

L2OPTIM

Linac 2 performance optimizer

User's Guide

Version 1.0

Note

This guide is part of the report "Linac 2 performance optimization" and is valid only with it. Further information can be found in the report.

Because of similarities, this guide refers to L2OPSIM the simulation program version, as well. Where differences are between the on-line program and the simulation it is indicated in the context.

I. Programs

L2OPTIM is a Fortran program to carry out on-line optimization on the equipment control parameters of the CERN/PS Linac 2 proton accelerator line so that the particle transmission in the linac improves. For this reason, it uses an analysis package, MINUIT, that sophisticatedly controls changes of the parameter values [5]. The program has been developed on the PS Unix platform IBM AIX/6000 machines and is available from the PS Program Library.

The version L2OPSIM has a similar program structure like the on-line one but the equipment related module is replaced with a simulation one, PARMILA [7]. The accelerator line structure that entirely corresponds to Linac 2 is read from a description data file. The program has been developed on Personal Computer platforms and is available from the PS/Hi PC Program Library.

II. Execution

The programs require command line options and an input file that specifies the equipment elements to be controlled and their initial control values. It produces output files with complete lists of all the input and output parameters. The file structures are described in the next section.

On-line version

The program has an option to run without modifying the control values, i.e., in data acquisition mode. To take statistically better measurements it is possible to preset a beam current averaging number in the command line, too.

Command syntax:

```
l2optim -<option> [n]
```

where the options and the numerical parameter are as follows:

- `-nowrite` This option causes the program not to modify any control parameters but take data acquisitions.
- `-write` This option causes the program to modify control parameters and take data acquisitions.
- `n` This parameter specifies the number of averaging over the same type of beam cycles. It accepts values from 1 to 100. The default is 10.

After starting the program a name list of the currently active beam cycles appears on the screen and prompts the user to enter one of them, which will appear in the output files under the label USER.

Simulation version

Due to no statistical beam fluctuation the simulation program version requests only a linac structure description file as a compulsory option.

Command syntax:

```
l2opsim <linacfile>
```

where the parameter is:

- `linacfile` This option specifies the name of the file that describes the linac structure and optionally the medium energy transport line in front of it. This must be a file as required by PARMILA.

III. Input-output files

The input-output file names are constants in the programs and begin with the terms L2OPTIM or L2OPSIM according to the version. The structure of the corresponding on-line and simulation files are very similar, usually the units of the data are different due to the different data representation. The following examples show L2OPTIM file contents used and created during a successful optimization.

Input file

L2OPTIM.IN

Data file of the equipment control parameters specified in the format requested by MINUIT (see the explanation of the example below or the corresponding MINUIT reference pages). In most of the cases it is enough to specify the names of the equipment elements and the programs automatically read the initial control values from the linac or from the corresponding structure file in case of simulation.

Example:

```

set title
OPTIMIZATION
parameters      value  step-size  lower-limit  upper-limit
1 'LI.QFN10'    0.0      5.0        -7.0         7.0
2 'LI.QDN20'    0.0      5.0        -7.0         7.0
3 'LI.QFN30'    0.0      5.0        -7.0         7.0
4 'LI.QDN40'    0.0      5.0        -7.0         7.0

simplex 200 0.00001
stop

```

Explanation:

Line #	Entry #	parameters: fixed / arbitrary
1	1.	Set title
2	1.	Any title
3	1.	parameters
	2.-	Any text
4 -		Equipment specifications:
	1.	Serial number (the max. number of equipment is 50)
	2.	Name of the equipment (the first 10 characters of the PS standard name of the equipment)
	3.	Parameter initial value P_i (if $P_i = 0$ then read from the
	4.	Parameter deviation (if $P_i = 0$ then it is % of read value)
	5.	Parameter lower limit (if $P_i = 0$ then it is % of read value)
	6.	Parameter upper limit (if $P_i = 0$ then it is % of read value)
n - 1	1.	simplex (a MINUIT minimization method)
	2.	Maximum number of optimization steps (approximately)
	3.	Maximal tolerable distance to the function minimum.*
n	1.	stop

* for example: if the function minimum is around 0.01 and 1% deviation is tolerable then the critical distance is ~ 0.0001 . If the estimated distance to the minimum is less then this value the program stops.

Output files

L2OPTIM.CCV It contains the current control parameter values set by MINUIT in each iteration step. The name of the beam cycle and the names of parameters are listed in the header.

L2OPTIM.OUT Output of the program containing the measured beam current values for each iteration step (find further explanation in the example below). The name of the beam cycle and the names of parameters are listed in the header.

L2OPTIM.MNT Output file of MINUIT with special information at different stages of the optimization (see the corresponding MINUIT pages).

Examples:

1. L2OPTIM.CCV

USER: MEAPSB					
INPAR	NAMES:	LI.QFN10	LI.QDN20	LI.QFN30	LI.QDN40
1:		197.1000	194.0000	148.0000	202.0000
2:		206.1381	194.0000	148.0000	202.0000
3:		193.2114	194.0000	148.0000	202.0000
		≈			
81:		193.4179	183.1985	138.1496	194.5532
82:		193.4170	183.1596	138.1635	194.9360
83:		193.4176	183.1888	138.1530	194.8012

This file lists the current control values after each optimization step for the parameters defined in L2OPTIM.IN.

2. L2OPTIM.OUT

USER: MEAPSB							
OPTPAR	NAMES:	TRA06	TRA07/06	TRA10/06	TRA30/06	TRA60/06	TRA60/10
1:		162.1966	91.7853	90.5155	88.5070	87.0219	96.1403
2:		162.7989	91.5105	89.7994	87.5948	85.7527	95.4936
3:		161.6835	91.7405	89.6739	87.4809	86.1543	96.0752
		≈					
81:		163.5894	94.3281	92.7312	90.2050	88.3818	95.3097
82:		164.0114	94.0201	92.5294	90.0981	88.8612	96.0356
83:		164.4156	93.9118	92.4830	89.8623	88.5816	95.7815

This file lists the corresponding beam acquisition values after each optimization step at five measurement positions. The first column lists the input beam currents at the entrance of Linac2 in mA. The following columns list the currents in percentage of the 1st value.

APPENDIX B

TRACE 3-D simulations

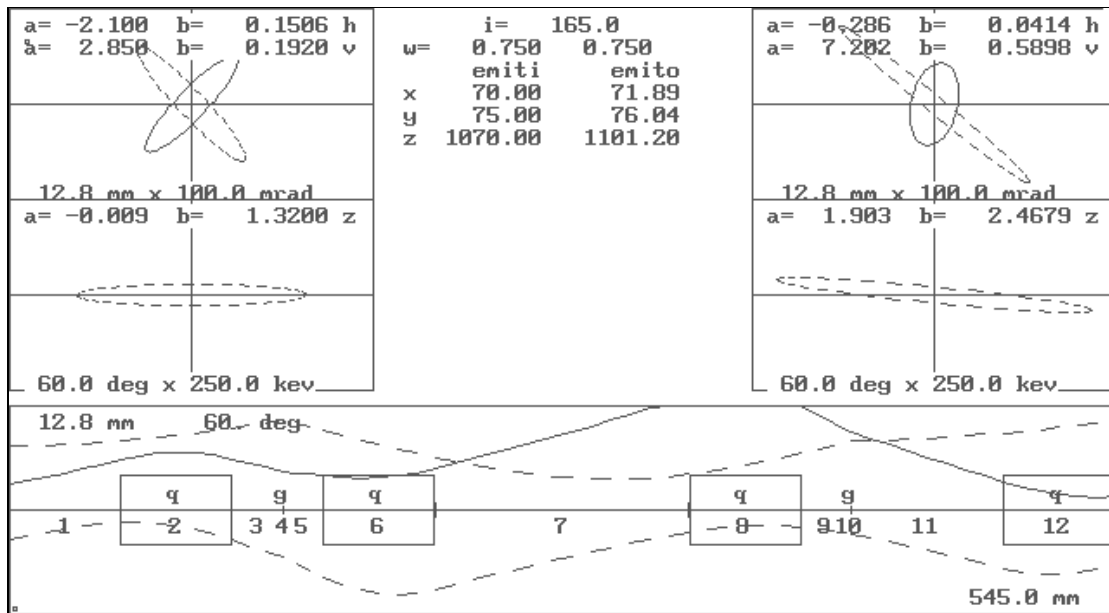
Note: the half aperture size of the beam pipes in the MEBT is 12.8 mm which is set as the range of the transport line drawings below.

1. MEBT with old setup

inputfile:

```
&data er= 938.260, q= 1., w= 0.750, xi= 165.000,
emiti(1)= 70.00, 75.00, 1070.00 norm= 0
beami(1)= -2.10, 0.1506, 2.85, 0.192, -0.0089, 1.320
freq= 202.0, pqext= 2.50, ichrom= 0,
xm= 12.80, xpm= 100.0, ym= 12.8, dpm= 60.0, dwm= 250.0, dpp= 60.0,
n1= 1, n2= 20, smax= 10.0, pqsmax= 2.0 ,mt=1
nt( 1)= 1, a(1, 1)= 55.0
nt( 2)= 3, a(1, 2)= 44.47 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 3)= 1, a(1, 3)= 25.0
nt( 4)= 10, a(1, 4)= 0.150 , -90.0 ,1.0 ,1.0 ,1.0
nt( 5)= 1, a(1, 5)= 20.0
nt( 6)= 3, a(1, 6)=-43.79 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 7)= 1, a(1, 7)=125.0
nt( 8)= 3, a(1, 8)= 33.40 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 9)= 1, a(1, 9)= 25.0
nt(10)= 10, a(1, 10)= 0.105 , -90.0 ,1.0 ,1.0 ,1.0
nt(11)= 1, a(1, 11)= 75.0
nt(12)= 3, a(1, 12)=-45.59 , 55.0 ,0.0000 ,0.0000 ,0.0000
&end
```

screen output:

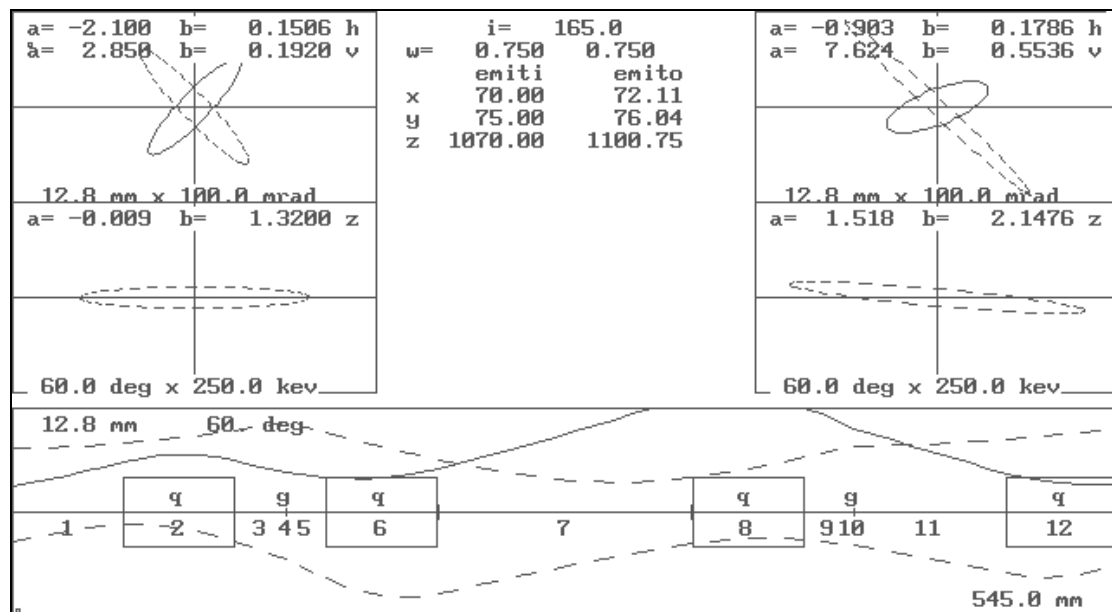


2. MEBT with new setup

inputfile:

```
&data er= 938.260, q= 1., w= 0.750, xi= 165.000,
emiti(1)= 70.00, 75.00, 1070.00 norm= 0
beami(1)= -2.10, 0.1506, 2.85, 0.192, -0.0089, 1.320
freq= 202.0, pqext= 2.50, ichrom= 0,
xm= 12.8, xpm= 100.0, ym= 12.8, dpm= 60.0, dwm= 250.0, dpp= 60.0,
n1= 1, n2= 20, smax= 10.0, pqsmax= 2.0 ,mt=1
nt( 1)= 1, a(1, 1)= 55.0
nt( 2)= 3, a(1, 2)= 43.65 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 3)= 1, a(1, 3)= 25.0
nt( 4)= 10, a(1, 4)= 0.150 , -90.0 ,1.0 ,1.0 ,1.0
nt( 5)= 1, a(1, 5)= 20.0
nt( 6)= 3, a(1, 6)=-41.35 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 7)= 1, a(1, 7)=125.0
nt( 8)= 3, a(1, 8)= 31.18 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 9)= 1, a(1, 9)= 25.0
nt(10)= 10, a(1, 10)= 0.105 , -90.0 ,1.0 ,1.0 ,1.0
nt(11)= 1, a(1, 11)= 75.0
nt(12)= 3, a(1, 12)=-43.97 , 55.0 ,0.0000 ,0.0000 ,0.0000
&end
```

screen output:



3. MEBT with losses

inputfile:

```
&data er= 938.260, q= 1., w= 0.750, xi= 165.000,
emiti(1)= 70.00, 75.00, 1070.00 norm= 0
beami(1)= -2.10, 0.1506, 2.85, 0.192, -0.0089, 1.320
freq= 202.0, pqext= 2.50, ichrom= 0,
xm= 12.8, xpm= 100.0, ym= 12.8, dpm= 60.0, dwm= 250.0, dpp= 60.0,
n1= 1, n2= 20, smax= 10.0, pqsmax= 2.0 ,mt=1
nt( 1)= 1, a(1, 1)= 55.0
nt( 2)= 3, a(1, 2)= 40.15 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 3)= 1, a(1, 3)= 25.0
nt( 4)= 10, a(1, 4)= 0.150 , -90.0 ,1.0 ,1.0 ,1.0
nt( 5)= 1, a(1, 5)= 20.0
nt( 6)= 3, a(1, 6)= -41.46 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 7)= 1, a(1, 7)= 125.0
nt( 8)= 3, a(1, 8)= 30.18 , 55.0 ,0.0000 ,0.0000 ,0.0000
nt( 9)= 1, a(1, 9)= 25.0
nt( 10)= 10, a(1, 10)= 0.105 , -90.0 ,1.0 ,1.0 ,1.0
nt( 11)= 1, a(1, 11)= 75.0
nt( 12)= 3, a(1, 12)= -45.75 , 55.0 ,0.0000 ,0.0000 ,0.0000
&end
```

screen output:

