MUSTAFA-A TOOL FOR NUMERICAL SIMULATIONS OF THE BEAM BEHAVIOR IN A LINAC

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Abstract

MUSTAFA stands for **MU**ltibunch **S**imulation and **T**racking **A**lgorithm for **F**uture linear **A**ccelerators and provides an environment for tracking a multibunch beam accelerated in the linac of a collider. It is made of three parts: i) an interactive utility MBUNCH which allows to run the simulations, edit the input data, systematically vary some parameters, launch statistics on misalignment realisations and select the outputs, ii) the tracking program itself MBTR that includes magnetic focusing, acceleration, wakefields, misalignments and trajectory correction, and iii) a graphics facility called MOVIE that provides an animated representation of the transverse motion within each bunch of a train, either in the geometric space or in the phase space. While MBTR is written in FORTRAN, the other two codes are written in QUICKBASIC (MS V4.5). They run on PC Pentium computers in a stand-alone mode, independent of any network. Hence MUSTAFA is easily transportable and offers a unique graphics facility. It has been extensively used for multibunch simulations in the Compact Linear Collider scheme (CLIC) as well as for demonstrations of the beam behaviour in different stability or beam break-up conditions.

1 INTRODUCTION

The transverse oscillations of many bunches under the influence of longitudinal and transverse wake fields are of fundamental importance for beam stability in linear colliders. Since these oscillations are governed by many coupled forced-oscillator equations, their behaviour is generally complex and not yet completely understood. Simulation codes therefore are important to analyse the question of the bunched beam stability for various sets of linac parameters. MUSTAFA provides a user-friendly environment for such a tracking and result analysis. Only a short description of the three parts of MUSTAFA is given below and the potential user is recommended to look at the published MUSTAFA description and users' guide [1] for more details.

2 TRACKING CODE MBTR

The central piece of the MUSTAFA codes which have been written for beam tracking and multibunch simulations in a linac is the FORTRAN program named MBTR. This program is based on the MBTRACK codes [2], issued themselves from the single bunch tracking application MTRACK [3]. MBTR is a result of an evolution that followed the needs related to the CLIC studies and emphasizes portability as well as graphical visualization.

Since the beam of a linear collider is highly relativistic, the space charge forces can be neglected and the longitudinal positions along the bunches are fixed (no mixing). This has two impacts on the beam model. The absence of radial forces makes the use of a 3D-model with macro-particles unnecessary and each bunch can simply be longitudinally divided into elements with constant relative positions. The main parts of the numerical model are described below:

– **The beam** is a train of equidistant bunches. Each bunch is divided in turn into equidistant slices of width δ_z, small w.r.to the r.m.s. bunch length σ_z. Each slice is defined by the transverse positions of its center of gravity and its r.m.s. transverse dimensions deduced from the emittances. The charge per bunch is distributed in all slices according to a (truncated) gaussian distribution.

– **Magnetic focusing** is achieved by quadrupoles arranged in a FODO lattice that also includes drifts, accelerating structures, beam position monitors (BPM) and microwave quadrupoles (RFQ). There are two versions of the MBTR code which only differ by the way the focusing is scaled along the linac with the energy of the bunches. The first version called MBTRSCAL corresponds to a continous and adiabatic scaling (small steps not requiring any matching) while the second called MBTRSECT gives a more realistic lattice implementation, that approximates to the continuous scaling solution but is based on linac sectors with constant FODO geometry, joined by matching insertions.

– **The RF system** is characterized by a few parameters, such as the RF frequency of the fundamental accelerating mode ω_{RF} in s^{-1}, the RF wave length λ_{RF} in m and the maximum amplitude of the loaded acceleration gradient G_a in MV/m. The relative position of the bunch train with respect to the RF wave is defined by the phase ϕ_{RF} of the reference slice of the first bunch which is equal to zero at the peak of the wave. The phase ϕ_{RF} can be different in each sector and adjusted for optimum BNS damping. The relative phases of all the slices of the bunches are then calculated from this reference value and from the z-position of each slice resulting from the beam definition.

– **Short-range wakefield** Green's functions are computed with the code MAFIA [4] and defined as usual via the loss factors k_n and frequencies $\omega_n/(2\pi)$ of a large number of synchronous modes. The short-range, delta-function wake potentials are then given by the subsequent summation over these structure normal modes [5].

– **Long-range wakefield** Green's function is obtained either from an analytical approximation or MAFIA output data, that directly provides the field in the time domain, i.e. as a function of the distance behind a point-charge. Different models can be used. They all assume that beam loading in a train of bunches is compensated, but they differ by the drop-off of the transverse wakefield behind bunch 1. Fig. 1 shows the Green's function of three particular models, two analytical ones based on piece-wise exponential decays and one numerical (termed here CG-DS) associated with individual damping of each cell and frequency detuning via linearly tapered iris dimensions. At the level of bunch 2, the wakefield is equal to 1 or 1.5 % of its maximum.

– The transport through the linac of the coordinates and geometrical emittances defined by the Σ matrix is done for every slice of each bunch, using the transfer matrices of the linac components. Hence, the slice emittance that includes the contribution of its off-set with respect to the average position of the train can be computed at any point s. Adding these contributions weighted by the slice population, gives the geometric emittance of a bunch or the whole train, depending on the selection. Calculating the (square root of the) determinant of Σ and multiplying by the Lorentz factor γ give the normalized bunch and beam emittances which are then used for further analysis.

– Trajectory correction is implemented in the presence of random misalignments of quadrupoles, accelerating structures and beam position monitors . It is based on a standard 'one-by-one' correction in which the beam is centred in a BPM by moving the preceding upstream quadrupole, taking into account the actual wakefields. A minimisation over several BPMs is also possible and errors in the measurements or in the displacements of the quadrupoles can be introduced.

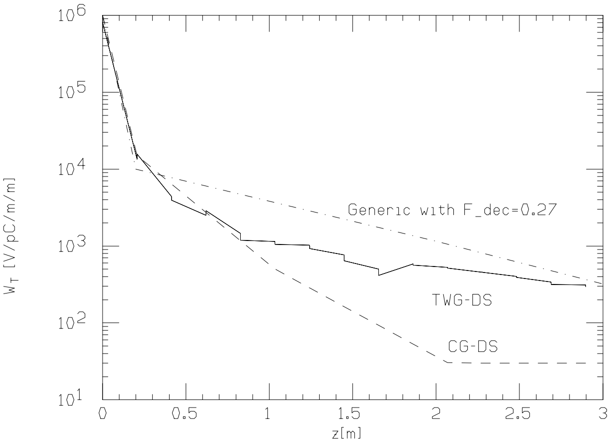

Figure 1: Long-range transverse wakefields in various CLIC structure models.

3 MBUNCH UTILITY

The MBUNCH program has been written to provide an effective and easy tool for working with the multibunch tracking code MBTR. It is fully menu driven and therefore self explanatory to a large extent, however, the basic parts are shortly described in this section.

MBUNCH handles the input and output of MBTR in an interactive way and allows to run the simulation code with specified input parameters. In addition, it postprocesses the output data providing both an online visualization of the results obtained and a statistical evaluation originating from many simulation runs. It also provides a link to the animated graphics facility which makes it possible to visualize a train of many bunches through the given linac. Finally MBUNCH gives the possibility to run either MBTRSCAL, the scaled lattice version of MBTR, or MBTRSECT, the sector lattice version of the simulation code (Section 2).

Like the simulation code MBTR, MBUNCH runs on IBM compatible PCs. It has been written using the language Microsoft Quickbasic V 4.5 [6] and is available in its executable form under the name MBUNCH.EXE. To run it efficiently together with MBTR and MOVIE, it is strongly recommended to use a PC with at least 16 Mbytes of internal RAM, a clock frequency of not less than 100 MHz, the available space on hard disk not being less than 30 Mbyte and a Pentium type processor. Although MBUNCH has been written under MSDOS (version 3.3 at least), WINDOWS 95 is well suited to run the code starting either in an MSDOS window or directly from Windows 95 Explorer.

The main menu of this program appears as:

```
 ****************************************
 *  MUSTAFA -MULTIBUNCH SIMULATION      *
 *      AND TRACKING ALGORITHM          *
 *                                      *
 *      G. GUIGNARD , J. HAGEL          *
 *                                      *
 *   (Version 1.0 , January 1998)       *
 ****************************************

Edit the input CLIC(SCAL)SECT.INP.... <===
Run the simulation .................
Look at the output summary .........
Look at the emittance graphs ........
Vary an Input parameter ............
Run the movie ......................
Save Results on Subdirectories ......
More ...............................
End ................................

Pick an option via the cursor UP/DOWN keys
and  execute the command with the ENTER key.
```

The first command enables the user to interactively change the input file via the KEDIT editor and displays a copy. The second command runs the requested simulation and produces the following files: i) a summary of the results with the echo of the input data that can be displayed via command 3, ii) four files containing the orbits and emittances as functions of position s for the first, an intermediate, and the last bunch as well as the whole train (graphs previewed with command 4, see example in Fig. 2. Command 5 varies any single input parameter within specified limits and steps, providing four files [as under ii)] with the vertical emittance versus this parameter, that can be displayed. The next command initiates the 'movie' (animated graphics) described below and the last one stores all the generated files in a sub-directory for later use. Commands 4 to 6 open (mostly self-explanatory) sub-menus.

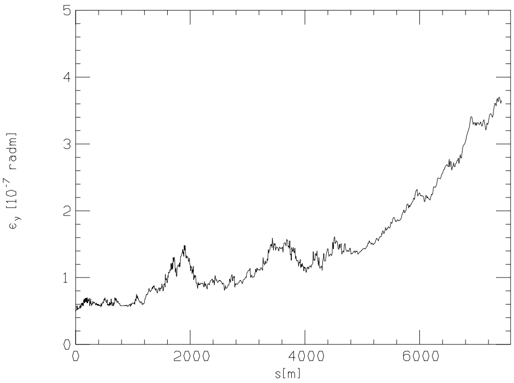

Figure 2: Vertical emittance growth averaged over a train of 10 bunches, along the 1 TeV linac, in the presence of a weak instability due to long-range wakefields

4 MOVIE FACILITY

The idea of the MOVIE code is to have a tool for direct visualization of transverse bunch oscillations as the train passes through all the parts of the linac. This helps to understand the instability mechanisms as well as the attempts to correct them. The MOVIE code shows the vertical oscillations (the most important for the flat beams of linear colliders) of all the slices of all bunches along the bunch coordinate z in the form of an animated graphics (real time corresponding to s). It uses an input file containing all the coordinates of all slices of all bunches along the entire linac (at every quadrupole position). This input file (CK.OUT) has to be created by the simulation code MBTR before MOVIE is run. Up to five bunches can be seen at any one time on the screen and it is possible during one run to scroll along the train using the right and left arrow keys. MOVIE van visualize bunches of up to 50 slices. The program MOVIE, as well as MBUNCH has been written using Microsoft Quick Basic (V. 4.5) [6] and can be run on any PC after importing and starting the executable file MOVIE.EXE. It can be run independently or via the MBUNCH utility which provides a comfortable way to launch it. The sub-menu for the ’movie’ appears as:

```
   MOVIE SHOWING THE MOTION OF THE
        BUNCHES IN THE LINAC

Use the File CK.OUT created by the
stand alone program ................ <===
Use a different File ...............
Run the Movie ......................
Preview the Frozen Pictures .........
Return to main menu ................
```

The proposed commands run the MOVIE facility from the last CK.OUT file created by MBTR simulations or from previously stored MOVIE-files with different names but the same extension. Command 3 initializes the animated graphics routine itself, requiring the full screen, using colors and displaying the bunch slice positions at successive quadrupoles at a nominal speed of 10 frames/s, giving the feeling of oscillating bunches with time when they travel down the linac (the related s-values appear on the screen).

The movie can be run with or without the subtraction of betatron motion, in the geometric- or phase-space, and offers on-line options to change the animation speed, stop on an image and save it in a file for later viewing with a graphics package. Figs 3 and 4 show examples of such frozen pictures in the geometric- and phase-space respectively, generated for a CLIC main beam. In the animated graphics, rapid succession of pictures of Fig.3-type gives the sensation of the oscillatory motion of the bunch tails. Colors are used to represent the particle gaussian distribution in a bunch (e.g. ’red’ for the dense core and ’blue’ for the tails).

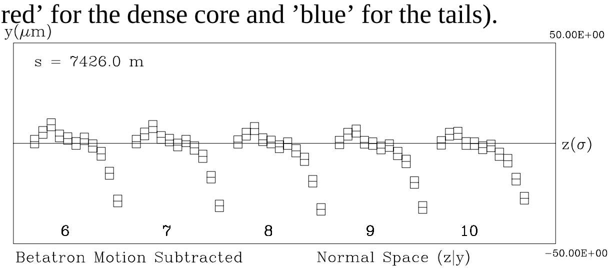

Figure 3: Vertical off-sets of the last five bunches at the linac end, for the same weak instability as in Fig. 2.

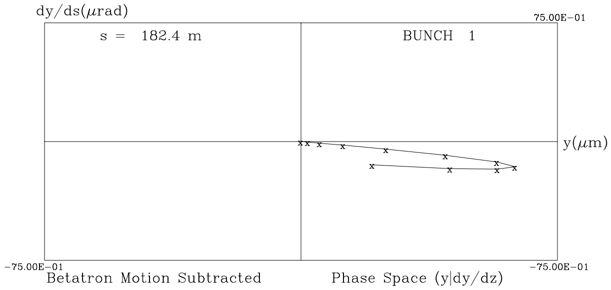

Figure 4: Vertical coordinate off-sets of bunch 1, in the phase space, at the linac beginning and with BNS damping.

5 CONCLUSION

The MUSTAFA programme ’trilogy’ has proved to be user-friendly and very useful for both the design of the CLIC linear collider and the definition of the required parameters or tolerances. It also provides a practical graphic illustration of the possible single-bunch or multi-bunch instabilities. Its modularity makes additions easy and its portability has showed to be extremely convenient when movie-examples are projected during seminars or conferences. The code is available on request to any potential user.

6 REFERENCES

[1] G.Guignard and J.Hagel, CERN-SL-98-002(AP), 1998.

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[5] A.Millich, CERN-SL-91-27(CO), 1991.

[6] J.R.Ottensmann, Quickbasic Quick Reference, Que Corporation, Carme, Indiana, 1988.